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AN EXPERIMENTAL INVESTIGATION INTO NO_X
CONTROL OF A GAS TURBINE COMBUSTOR AND
AUGMENTOR TUBE INCORPORATING A
CATALYTIC REDUCTION SYSTEM

by

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March 1990

Thesis Advisor: D.W. Netzer

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An initial experimental investigation was conducted to examine the feasibility of NOx emission control using catalytic reduction techniques in the jet engine test cell environment. A modified T-63 gas turbine combustor and an augmentor tube, 21 feet in length and containing a perlite catalyst, were used as a gas generator and catalytic reduction system. Four data runs were made. Three runs were completed without the catalyst installed. Temperature and velocity profile measurements were obtained in order to calculate augmentation ratios for different engine fuel to air ratios. NOx, CO, and unburned hydrocarbon concentrations in the exhaust were measured to provide a baseline for further tests. A fourth data run was made with the perlite catalyst installed in the augmentor tube. A 64 percent NOx reduction was observed, however the large pressure drop across the catalytic bed deemed the current configuration impractical. Recommendations for alternative configurations are

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An Experimental Investigation Into NO_x Control
of a Gas Turbine Combustor and Augmentor Tube
Incorporating a Catalytic Reduction System

by

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Submitted in partial fulfillment
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ABSTRACT

An initial experimental investigation was conducted to examine the feasibility of NO_x emission control using catalytic reduction techniques in the jet engine test cell environment. A modified T-63 gas turbine combustor and an augmentor tube, 21 feet in length and containing a perlite catalyst, were used as a gas generator and catalytic reduction system. Four data runs were made. Three runs were completed without the catalyst installed. Temperature and velocity profile measurements were obtained in order to calculate augmentation ratios for different engine fuel to air ratios. NO_x, CO, and unburned hydrocarbon concentrations in the exhaust were measured to provide a baseline for further tests. A fourth data run was made with the perlite catalyst installed in the augmentor tube. A 64 percent NO_x reduction was observed, however, the large pressure drop across the catalytic bed deemed the current configuration impractical. Recommendations for alternative configurations are presented. The results of the investigation have proven that further study is warranted.

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NOMENCLATURE

AR	Augmentation ratio
cm	Centimeters
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
D	Diameter
DACU	Data acquisition and control unit
EPA	Environmental Protection Agency
f	Fuel to air ratio
F	Fahrenheit
Fe_2O_3	Iron oxide
GFC	Gas filter correlation
GPM	Gallons per minute
HP	Hewlett-Packard
m	Mass flow rate
mV	Millivolts
NO	Nitric oxide
NO_x	Nitrogen oxides
NO_2	Nitrous oxide
NPS	Naval Postgraduate School
N_2	Nitrogen
O_3	Ozone

P	Pressure
ppm	Parts per million
psi	Pounds per square inch
R	Rankine
SCFH	Standard cubic foot per hour
SFRJ	Solid fuel ramjet
T	Temperature
UHC	Unburned hydrocarbon
V	Velocity

Subscripts

a	Air
augup	Upstream of catalyst position in augmentor tube
avg	Average value across augmentor tube
bp	Bypass
c	Combustor
ex1	Upstream of quench air in combustor
t	Stagnation/total

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I. INTRODUCTION

With continually increasing worldwide industrialization and the resulting further destruction of natural cleansing agents, environmental concerns and pollution control are currently of paramount importance and they will continue to be so into the future. A major portion of the total sources of pollutants are the particulate and gaseous products of combustion. There are four principle chemical classes of these pollutant species which have the largest impact:

1. Nitrogen oxides (NO_x)

2. Carbon monoxide (CO)

3. Organic compounds (unburned or partially burned hydrocarbons (HC) or soot)

4. Sulfur oxides (SO_x). [Ref. 1]

These combustion species can also be described as either primary pollutants, which are emitted directly to the atmosphere (soot or nitric oxide, NO) or secondary pollutants which are formed by chemical/photochemical reaction of primary pollutants after being emitted into the atmosphere and exposed to sunlight (i.e., ozone, O_3) [Ref. 2]. Some pollutants fall into both categories such as nitrous oxide (NO_2), which is emitted directly from combustion exhausts but is also formed in the atmosphere photochemically from nitric oxide (NO).

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Of the total nitrogen oxides (NO_x) emitted from engine exhaust, about 90% is NO which oxidizes to NO_2 in the atmosphere. In the presence of sunlight, NO_2 decomposes photochemically to give atomic oxygen (O) which combines with molecular oxygen (O_2) to give ozone (O_3). The reaction of ozone with other hydrocarbons in the atmosphere forms carbon dioxide (CO_2) and other secondary products which result in photochemical smog or a brownish discoloration of the atmosphere. [Ref. 3]

The U.S. Navy and U.S. Air Force have been very interested in studies looking for economical alternatives in controlling pollution emissions, specifically soot and NO_x emissions from their gas turbine engine test cells (which are used in research and engine performance recertification after a rework or overhaul). As new generation engines exhibiting somewhat higher exhaust temperatures and pressure ratios are introduced, it can be expected that they will produce more NO_x emissions than current engines. For civilian aviation, such emission standards are set by the Environmental Protection Agency (EPA) and will most likely become more stringent in the future. The overall objectives of these efforts are to reduce the emission of NO_x and other pollutants, minimize the damage to the atmosphere and satisfy current state and EPA regulations.

Commonly, gas turbine engine test cells are comprised of an instrumented static test stand, an augmentor tube, and a vertical exhaust stack. The augmentor tube provides an enclosure to reduce the velocity and temperature of the exhaust, enable potential engine noise suppression, and provides a capability to physically "treat" the exhaust gases, while the exhaust stack vents the gases into the atmosphere.

Currently, NO_x emission control is envisioned to use some type of catalytic reduction process within the augmentor tube. This could involve a technique combining the injection of some substance (i.e., ammonia or isocyanic acid [Ref. 4,5,6]) into the exhaust flow inside the augmentor tube and a catalytic surface (i.e., iron oxide, perlite, or vermiculite [Ref. 7]) installed inside the tube further downstream. This technique of NO_x control centers around the chemical treatment of the combustion products or exhaust of the engine. The introduction of fuel additives in the engine (thereby changing the combustion species in the exhaust) and the use of staged combustion have also been studied, but will not be addressed here.

Previous research at the Naval Postgraduate School since 1982 has primarily focused on the effects of fuel composition and additives on engine exhaust particulate emissions or solid soot concentrations (as last reported in 1988 by Lindsay [Ref. 8]). Lindsay's research utilized an actual Allison T-63-A-5A

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engine combustor section modified to allow the use of nonintrusive, optical techniques (three wavelength transmittance/forward laser light scattering measurements) to measure the actual size and concentration of solid exhaust particles (soot) across the combustor and augmentor tube.

Conversely, a primary goal of this research was to investigate an effective NO_x control process, entailing a combination of exhaust treatment techniques, to accommodate the operational ranges and variables experienced in the gas turbine engine test cell environment. The challenge exists in determining an overall NO_x control strategy since catalytic reduction has been found to be very temperature dependent. In addition, the technique must be applied without severely compromising the proper functioning of the test cell (pressure drop, augmentation ratio, etc.). This makes it particularly difficult to apply to different engines, engine power settings, and corresponding augmentation ratios in the gas turbine engine test cell environment. Previous research at the Naval Postgraduate School has not touched upon this concept before, but it has been under study by the U.S. Air Force, at the Naval Air Propulsion Center, and at other government laboratories and agencies.

Recent studies have observed greater amounts of CO (700 ppm at idle to 45 ppm at 75% power) and unburned hydrocarbons (950 ppm at idle to 3 ppm at 75% power) at low gas turbine

power settings. At high power settings, larger amounts of NO_x (10 to 60 ppm) and smoke have been observed. The general trend reflects that high concentrations of NO_x are not normally present together with high levels of CO. In afterburner, gas turbine engines may emit much higher concentrations of both CO (900 ppm) and NO_x (80 to 100 ppm) [Ref. 7].

The variation of concentrations with power settings and other variables in the test cell environment confirms the difficulty which exists in providing an efficient NO_x control process over all operating conditions. To date, studies indicate that NO_x reductions of up to 90-100% are possible depending on catalytic bed temperatures, catalyst volume and composition, and engine power setting [Ref. 7].

At the outset, the scope and following objectives were set for this investigation utilizing the Allison T-63 combustor as a gas generator.

1. Re-plumb all fuel and air lines and re-instrument the T-63 engine and ensure the engine, associated hardware and software operate satisfactorily.

2. Design and build a test stand for the 21 foot augmentor tube.

3. Install and calibrate a new gas sample dilution and conditioning unit, NO_x analyzer, carbon monoxide analyzer, and unburned hydrocarbon (UHC) analyzer.

4. Determine the average velocity, temperature, and mass flow rate of the gas exhaust at the end of the augmentor tube prior to the installation of the catalytic bed.

5. Install an iron oxide (Fe_2O_3) catalytic bed (available from the Von Didier-Werke Corp., West Germany) at the aft end of the augmentor tube and determine the effect of the catalytic bed on NO_x, CO, and UHC concentrations, augmentation ratio, and pressure drop as the combustor exhaust passes through the bed.

6. Measure the concentrations of NO_x, CO, and UHC before and after the catalyst while varying the augmentation ratio, engine exhaust temperature, and engine fuel to air ratio to determine the practicality of using such a technique in the gas turbine test cell environment.

II.   EXPERIMENTAL APPARATUS

A.   COMBUSTOR

A full scale Allison T-63-A-5A Gas Turbine combustor (Figures 1 and 2), as modified by Grafton [Ref. 9] was used to generate jet exhaust gases. Grafton [Ref. 9] installed a quench manifold forward of the exhaust nozzle and just aft of the turbine nozzle block to simulate the temperature drop of the combustor exhaust gases which would normally take place upon turbine work extraction. In this investigation, the quench air to the manifold was supplied at approximately 20 deg. F (480 deg. R) and at a flow rate of between 0.5 and 0.6 lbm/sec. The required quench air was supplied from a single air line branching off from the main air line through a sonic choke (D_{bp} = 0.237 in.) sized to provide a 0.5 lbm/sec flow rate assuming a minimum of 475 psi air pressure was provided upstream of the choke. The quench air line branch was located prior to the main air sonic choke and vitiated air heater. New combustor ignitor and air heater torch transformers were also obtained and installed prior to the experiments.

The combustor apparatus used in this experiment was moved from the test cell utilized by the Lindsay experiment [Ref. 8], necessitating installation of all new fuel and air lines as well as re-instrumentation of the combustor. Prior to
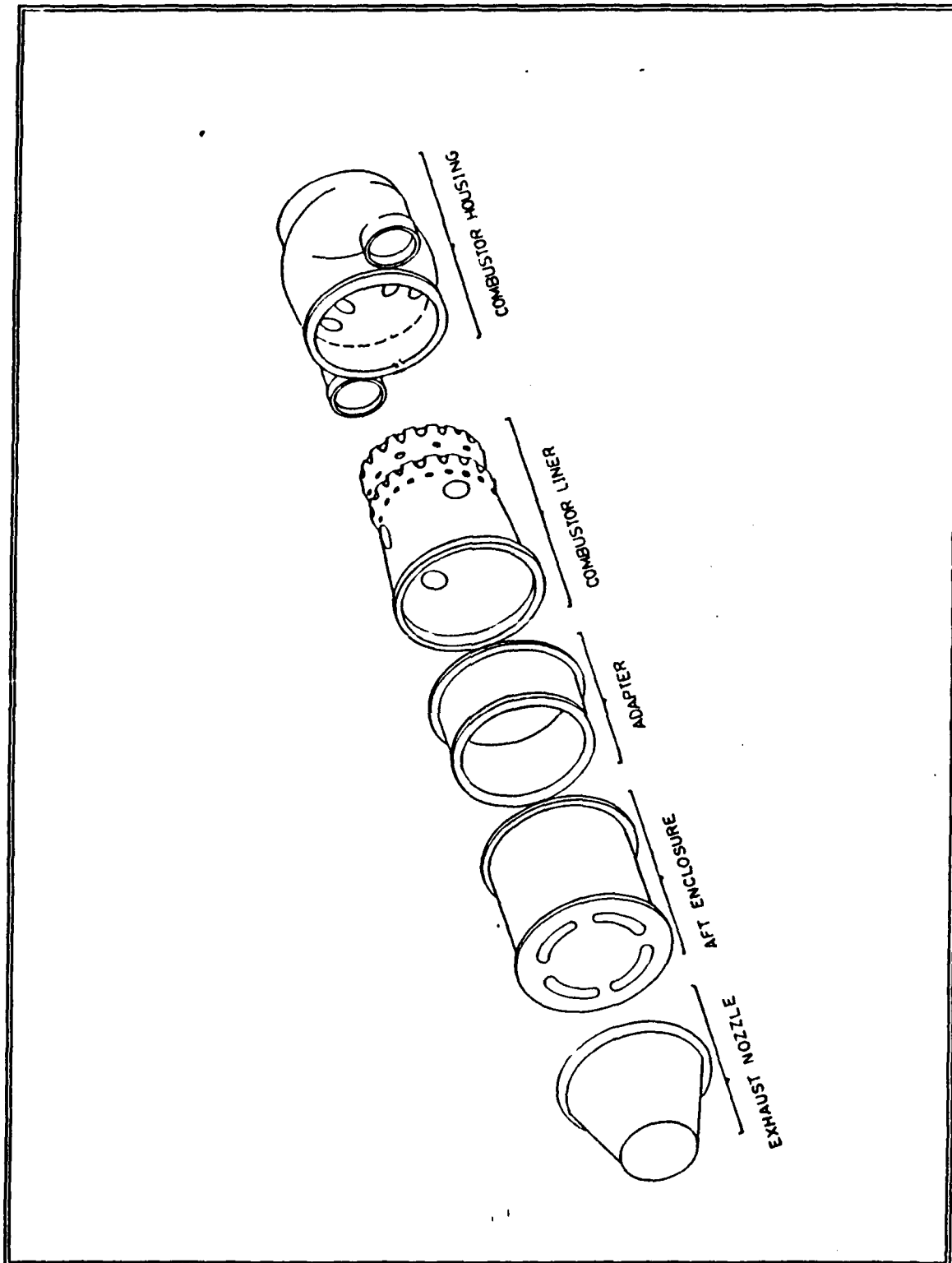
Figure 1. Schematic of T-63 Combustor Components
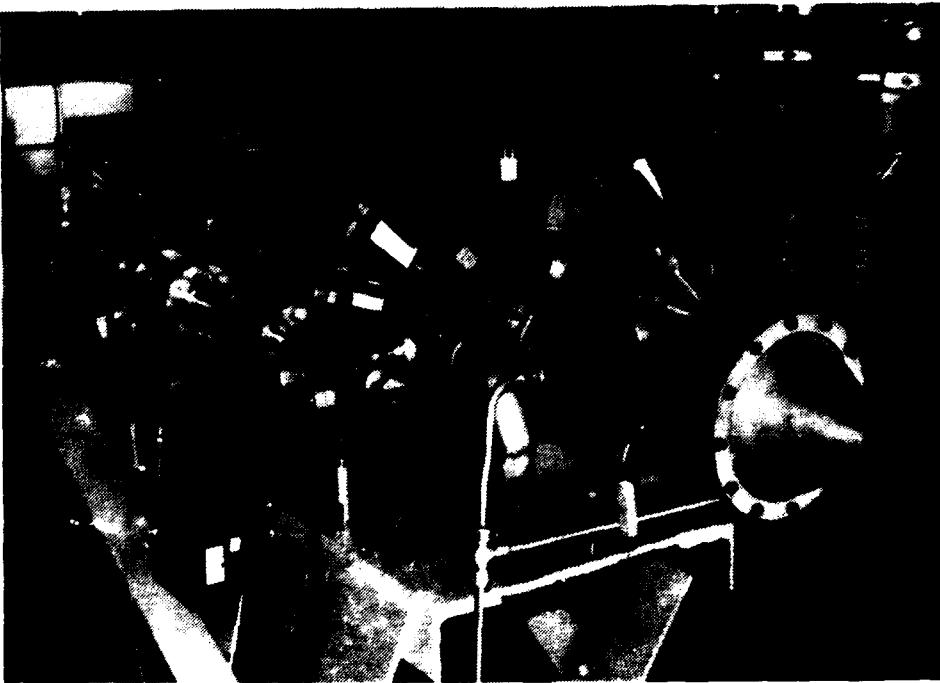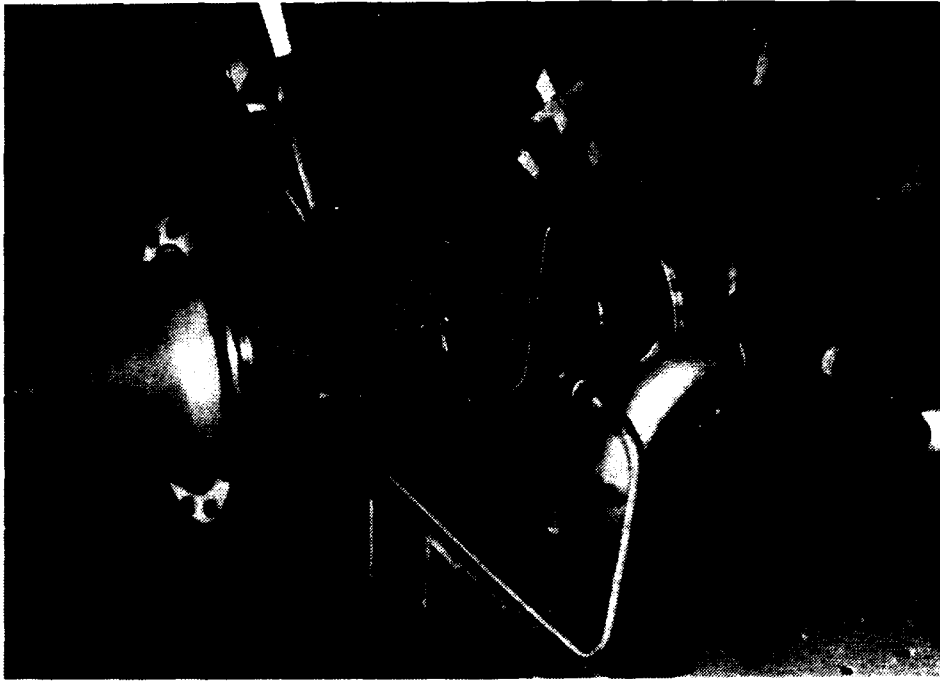
Figure 2. Photographs of T-63 Gas Turbine Combustor

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initial engine test and data runs, all fuel and air lines were leak tested under high pressure.

Pertinent T-63 engine data is provided below in Table I at standard sea level static conditions.

Table I. T-63 PERFORMANCE RATINGS [Ref. 10]

Rating	f	m_{air} (lb/s)	m_{fuel} (lb/s)	T_t (deg F)
Takeoff	0.019	3.17	0.061	1380
Military	0.019	3.17	0.061	1380
Normal	0.017	3.04	0.053	1280
90% Normal	0.017	2.95	0.049	1226
75% Normal	0.015	2.82	0.043	1148

Note: compressor ratio = 6.25, P_c = 92 psia
      engine length = 40.4 in, height = 22.5 in,
      width = 19.0 in, dry weight = 138.7 lb.

B. AIR SUPPLY

Compressed air for the combustor and quench manifold was provided from a 3000 psi tank storage system (Figure 3). Compressed air was supplied to the tank system using two compressors with an in-line air drier system to remove moisture. Air flowed from the tanks, through several valves, to a dome loaded pressure regulator operated from the system control panel inside the control room. The dome loaded pressure regulator provided a stable pressure to the main air sonic choke (D_a = 0.42 in.), which when instrumented with a

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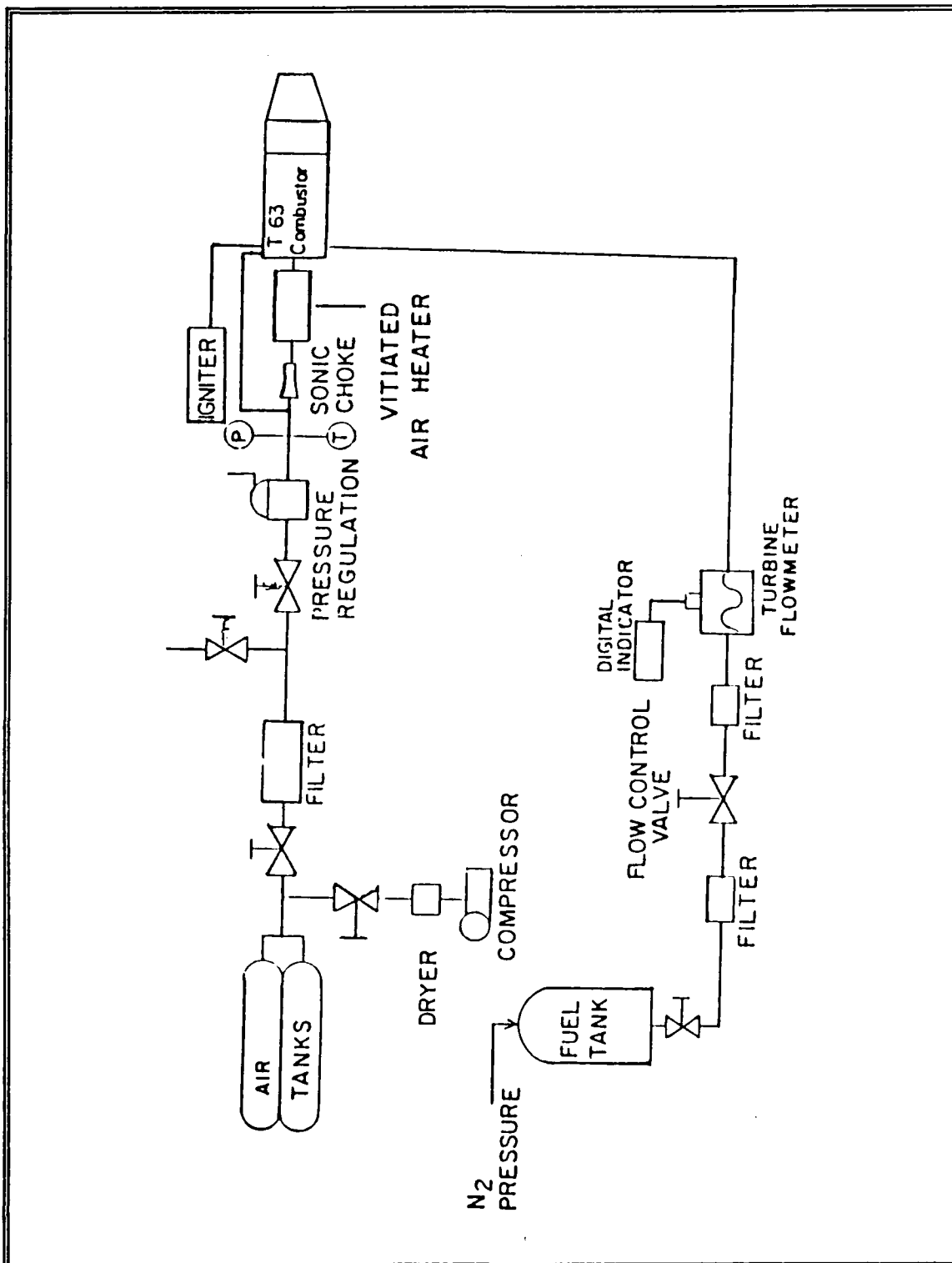
Figure 3. Schematic of Air and Fuel Supply Systems (Adapted from [Ref. 11]).

thermocouple and pressure transducer was used by the computer to determine the air mass flow rate to the combustor. The sonic chokes were sized to obtain an approximate 1.7 - 1.9 lbm/sec mass flow rate of primary air, 0.5 lbm/sec of quench air, and a 90-100 psi combustor chamber pressure. The quench air branch was located after the dome loaded pressure regulator and prior to the main air sonic choke.

C. VITIATED AIR HEATER

A vitiated air heater was installed between the main inlet air sonic choke and the inlet of the combustor, providing a means to vary the combustor inlet temperature. An ethylene charged ignitor torch was used to start the hydrogen fueled air heater. Make-up oxygen was added downstream of the air heater prior to entering the combustor inlet. This oxygen was added to replace the oxygen burned in the air by the vitiated air heater, ensuring that the correct molar/mass composition of inlet oxygen and nitrogen entered the combustor. The torch and heater gas introduction into the main air and vitiated air heater was controlled via solenoid valves remotely activated from the control room.

Sonic chokes were placed in the lines between the heater fuel and make-up oxygen gas bottles and the point of injection into the vitiated air heater. The chokes were sized assuming an air heater pressure of 250 psi and hydrogen fuel to air

of 0.0015, yielding an air heater temperature of 860 deg. Rankine. Using the one dimensional, isentropic flow expressions with fixed properties, the heater fuel and make-up oxygen sonic choke diameters were determined to be 0.035 and 0.070 inches respectively.

D. FUEL SUPPLY

A remotely controlled, pressurized 20 gallon tank provided fuel to the combustor. Nitrogen was used to pressurize the tank using a remotely controlled dome loaded pressure regulator. From the tank, NAPC #4 (Suntech 4) fuel was supplied through a series of filters, through a throttle valve in the control room, into a turbine flowmeter, to an electric solenoid shutoff valve and into the combustor (Figure 3). Fuel flow rate, in gallons per minute, was available from a digital display in the control room and was provided to the HP data acquisition system via the HP 3497 DACU scanner channel 25. The displayed flow rate was the result of the output of the turbine flowmeter.

E. THERMOCOUPLES AND PRESSURE TRANSDUCER INSTRUMENTATION

Chromel-Alumel (Type K) thermocouples were used to measure the various temperatures in the high pressure air lines and combustor as well as inside the augmentor tube. The thermocouple and pressure transducer outputs were provided to the Hewlett-Packard (HP) 3497 Data Acquisition/Control Unit

(DACU) of the HP-3054A data acquisition system for recording and flow rate calculations. The following provides a summary of thermocouple and transducer locations and their associated data acquisition scanner channel number used to input the measurements into the microcomputer:

VARIABLE	HP-3497 DACU CH NUMBER
P_a (main air pressure)	24
P_c (combustor chamber pressure)	23
P_{hf} (heater fuel, H_2 pressure)	22
P_{ho} (heater make-up oxygen pressure)	21
T_a (main air temp)	60
T_{cin} (combustor inlet air temp)	61
T_{ex1} (combustor exhaust upstream of quench)	62
T_{ex2} (combustor exhaust downstream quench)	63
T_{ho} (heater make-up oxygen temp)	64
T_{hf} (heater fuel temp)	65
T_{augup} (augmentor tube, upstream of catalyst)	66
T_{augd1} (augmentor tube, downstream catalyst)	67
T_{augd2} (augmentor tube, downstream catalyst)	68

F. AUGMENTOR TUBE AND INSTRUMENTATION

An augmentor tube, 21 feet long and two feet in diameter, (Figure 4) was used during the experiment. The tube was suspended on a rigid castor system mounted on a heavy stand constructed of four-inch angle iron. The castor system

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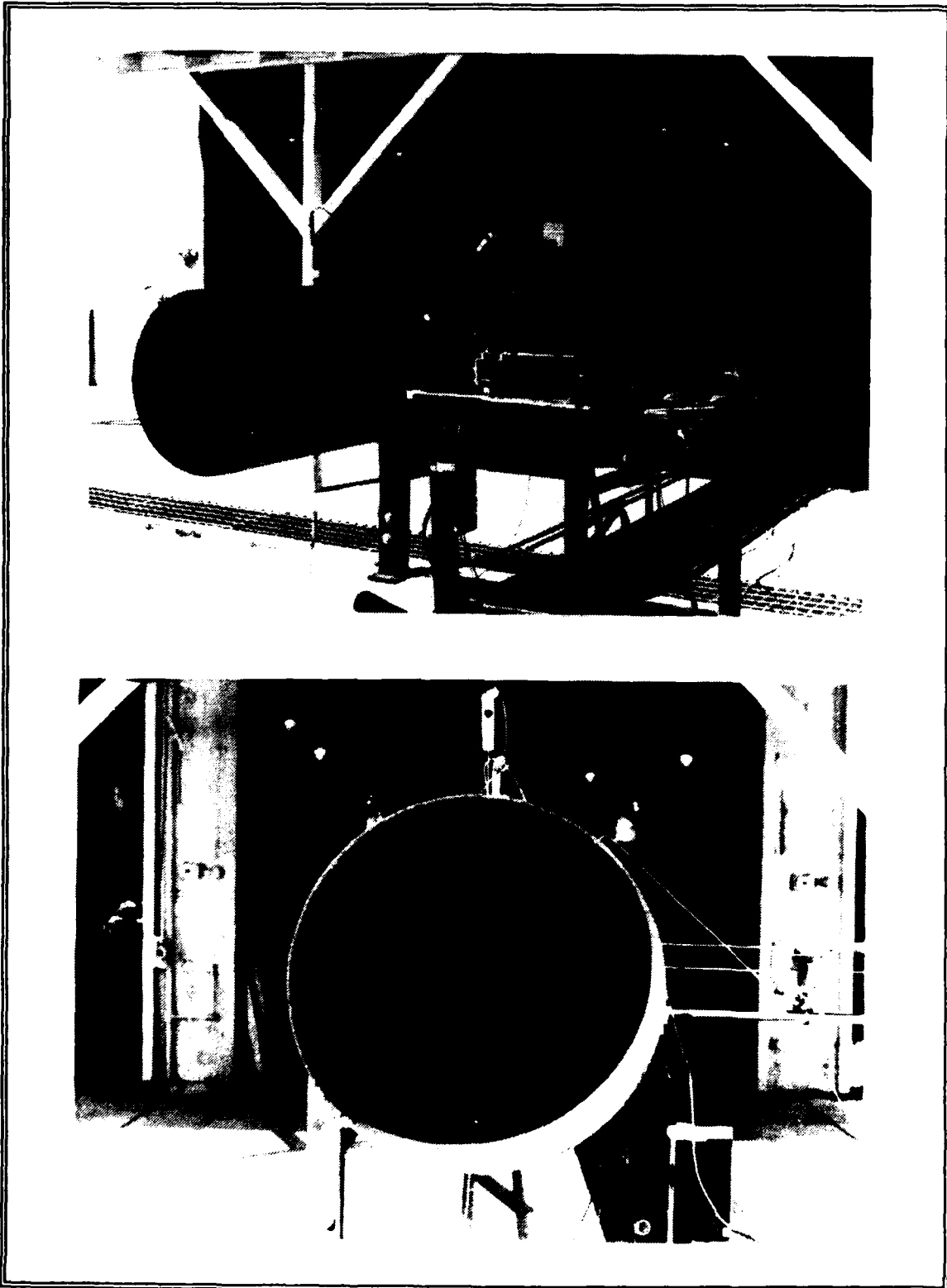
Figure 4. Photographs of Augmentor Tube on Stand

enabled the augmentor tube to be slid into the proper position for each data run from its storage position. The purpose of the tube was to capture the primary jet exhaust of the T-63 combustor, mix the exhaust with inducted ambient air, and enable the air mixture to be treated by the catalyst located inside the augmentor tube, 4.5 feet from the exit. Gas samples were taken prior to and after the catalytic bed to determine the effectiveness of the catalyst in scrubbing the exhaust of NO_x.

A variable diameter blocking plate was attached at the forward end of the augmentor tube at the T-63 exhaust (Figure 5). Varying the opening diameter of the tube enabled a variable augmentation ratio, i.e., the ratio of the induced ambient air (air drawn into the tube by the jet exhausting into the tube) flow rate to the T-63 exhaust flow rate (Figure 6). This in turn created variable amounts of colder ambient air induction into the tube to viscously mix with the T-63 exhaust gases, and also provided the required cooler catalyst inlet and augmentor exhaust temperatures. For this experiment, a five inch diameter orifice plate was attached to the blocking plate.

In order to determine the total mass flow through the augmentor tube, an average velocity and temperature near the exit of the tube had to be measured. To find the velocity, static and stagnation pressures were obtained 30 inches from
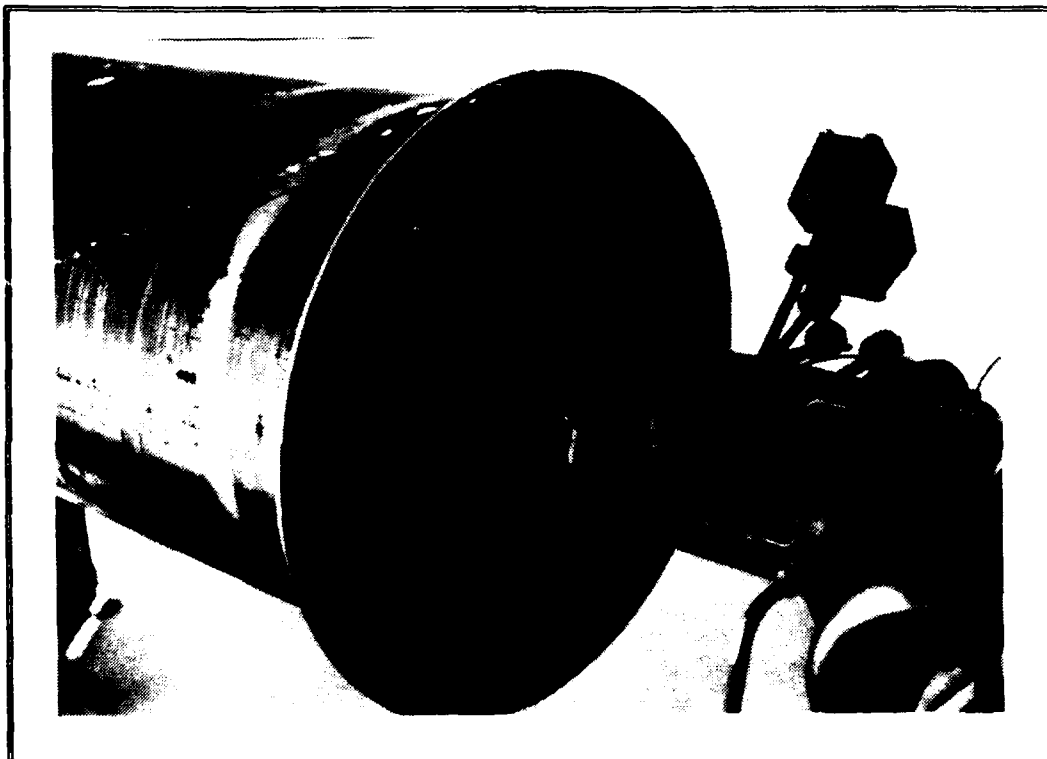
Figure 5. Photograph of Variable Diameter Blocking Plate
Installed on Front of Augmentor Tube
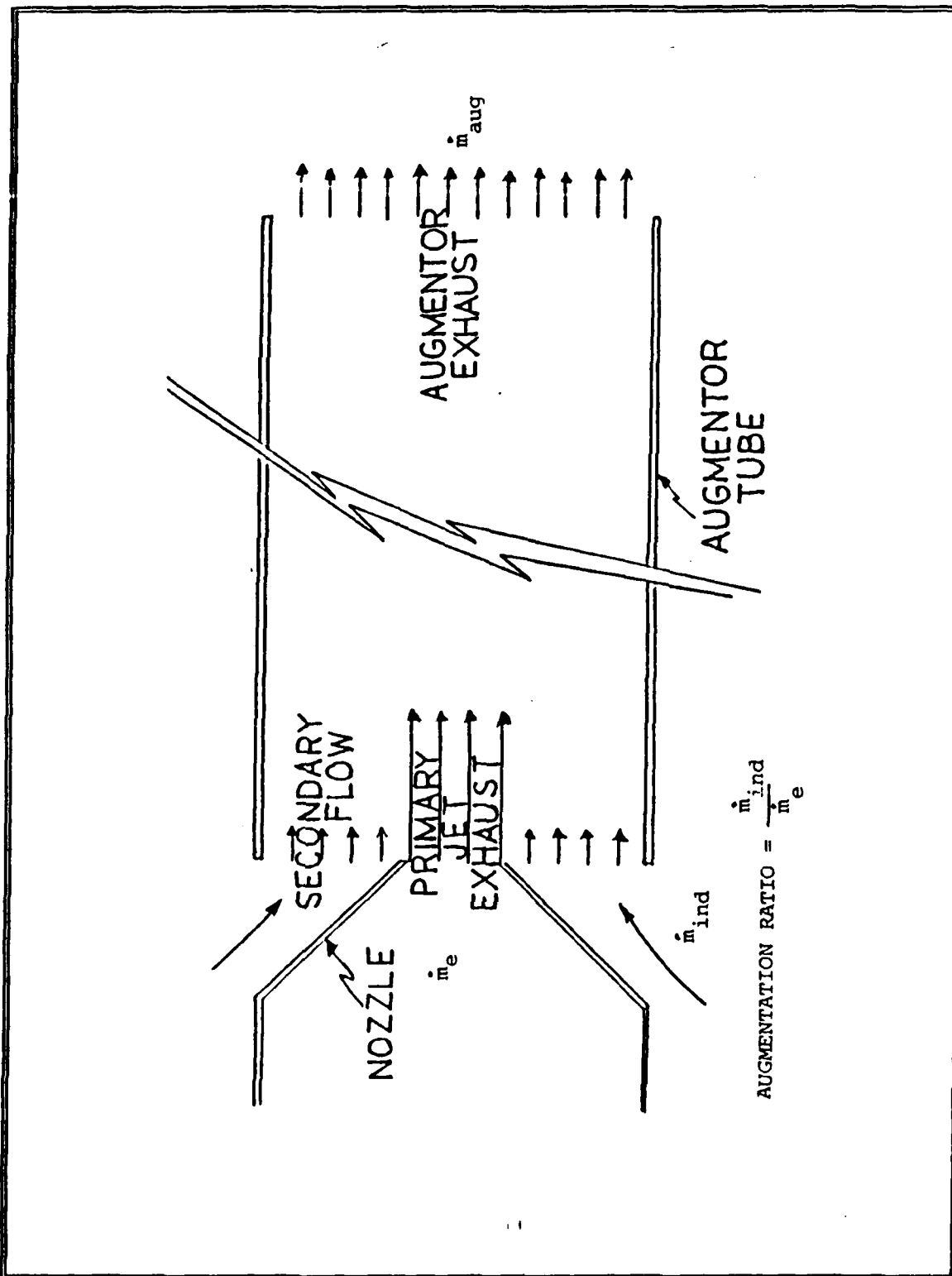
Figure 6. Augmentor Tube Flow [Ref. 12]

the exit plane of the augmentor tube. Static pressure was measured with an eighth-inch static port installed flush with the inside of the tube. The stagnation pressure across the tube radius was obtained with a modified United Sensor KT-18-C/A-12-C Kiel probe (Figure 7) enclosed within a 0.375 inch stainless steel tube. The Kiel probe was mounted on an electric motor-driven traversing platform (Figure 8) mounted on an adjustable stand. The Kiel probe was introduced into the flow through an orifice in the wall of the augmentor tube. The probe could extend from 2.5 inches from the wall to the tube centerline at 11.75 inches. The traversing Kiel probe was controlled by a DC motor speed control box in the control room. Low pressure transducers on the adjustable stand were connected through Pacific amplifiers into an Omega strip chart recorder for recording static and total pressure as well as probe position in the augmentor tube.

Figure 9 provides a schematic of the augmentor tube and associated instrumentation including thermocouple, catalyst basket, and sample gas probe locations.

G. CATALYTIC BED

A stainless steel, circular basket was manufactured to enable different varieties of catalyst species to be inserted into the augmentor tube. The enclosure (Figure 10) was 23.25 inches in diameter and five inches wide, producing a maximum
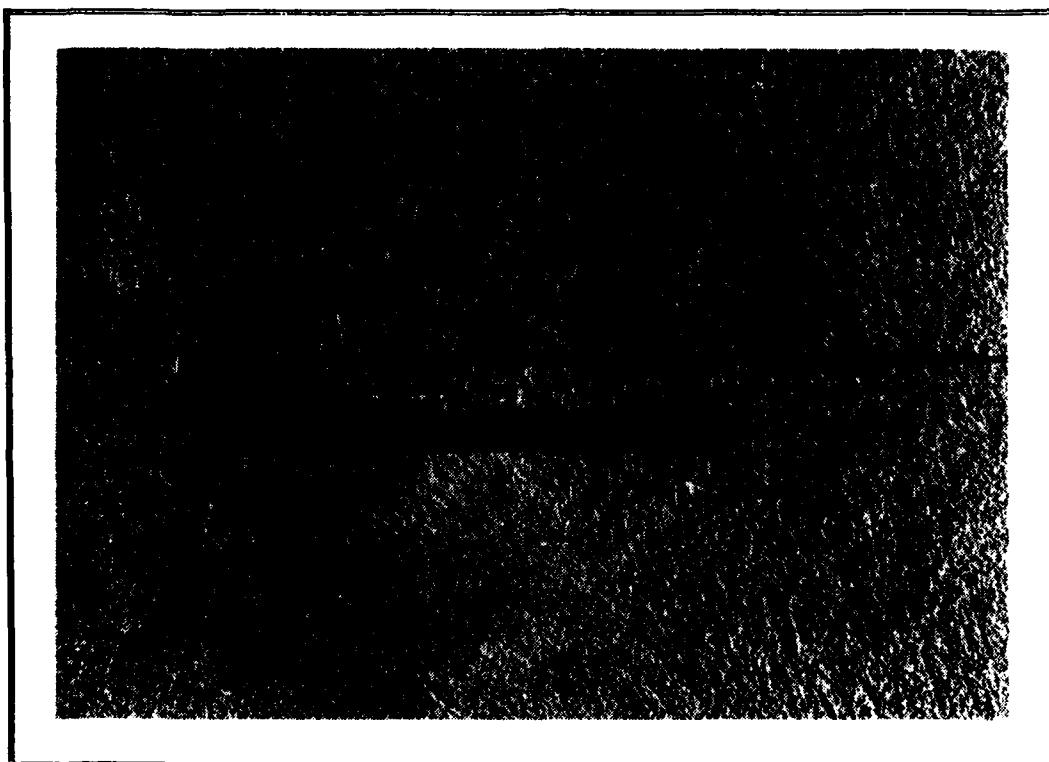
Figure 7. Photograph of Kiel Stagnation Pressure Probe
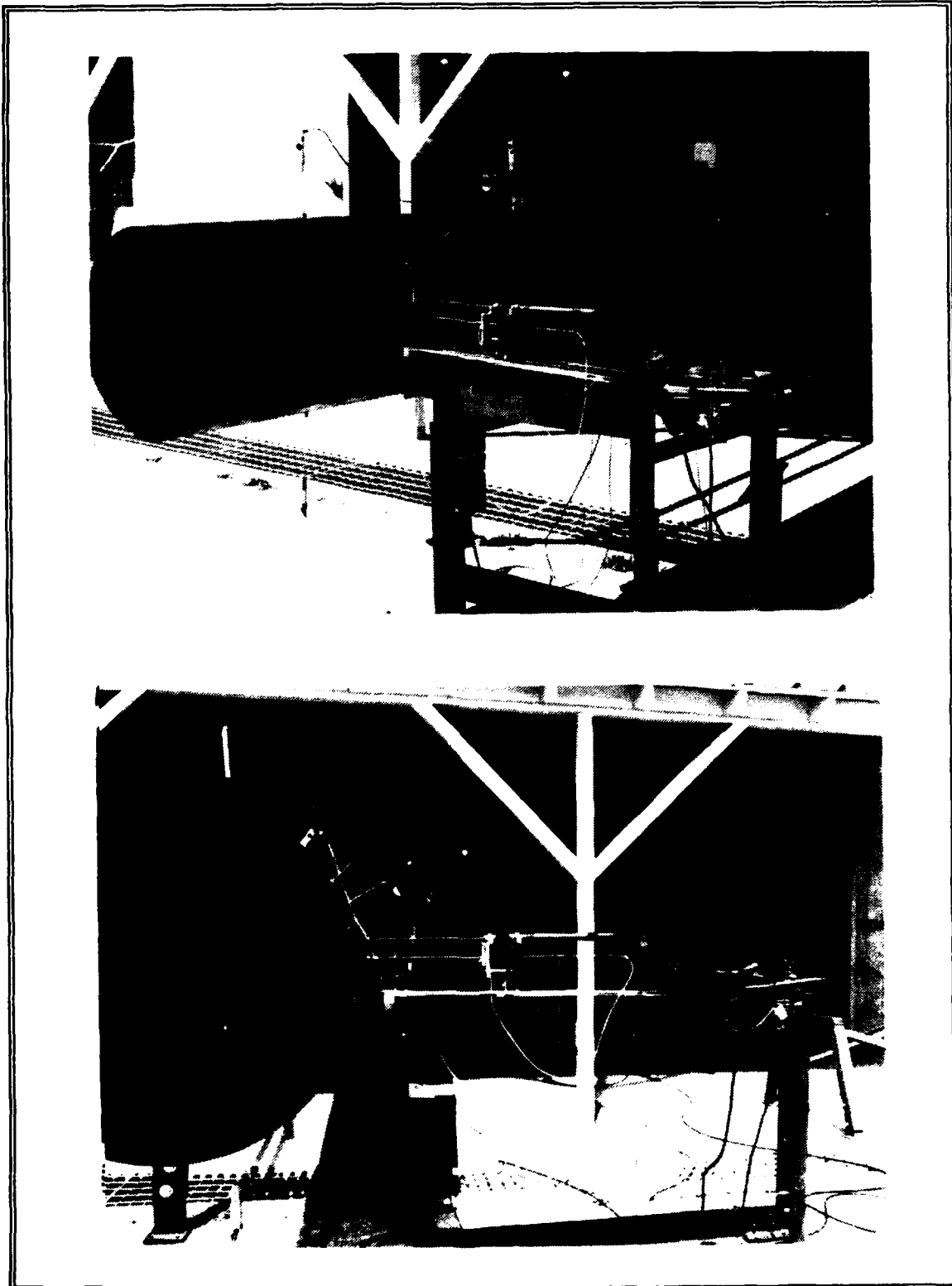
Figure 8. Photographs of Kiel Probe on Traversing Stand

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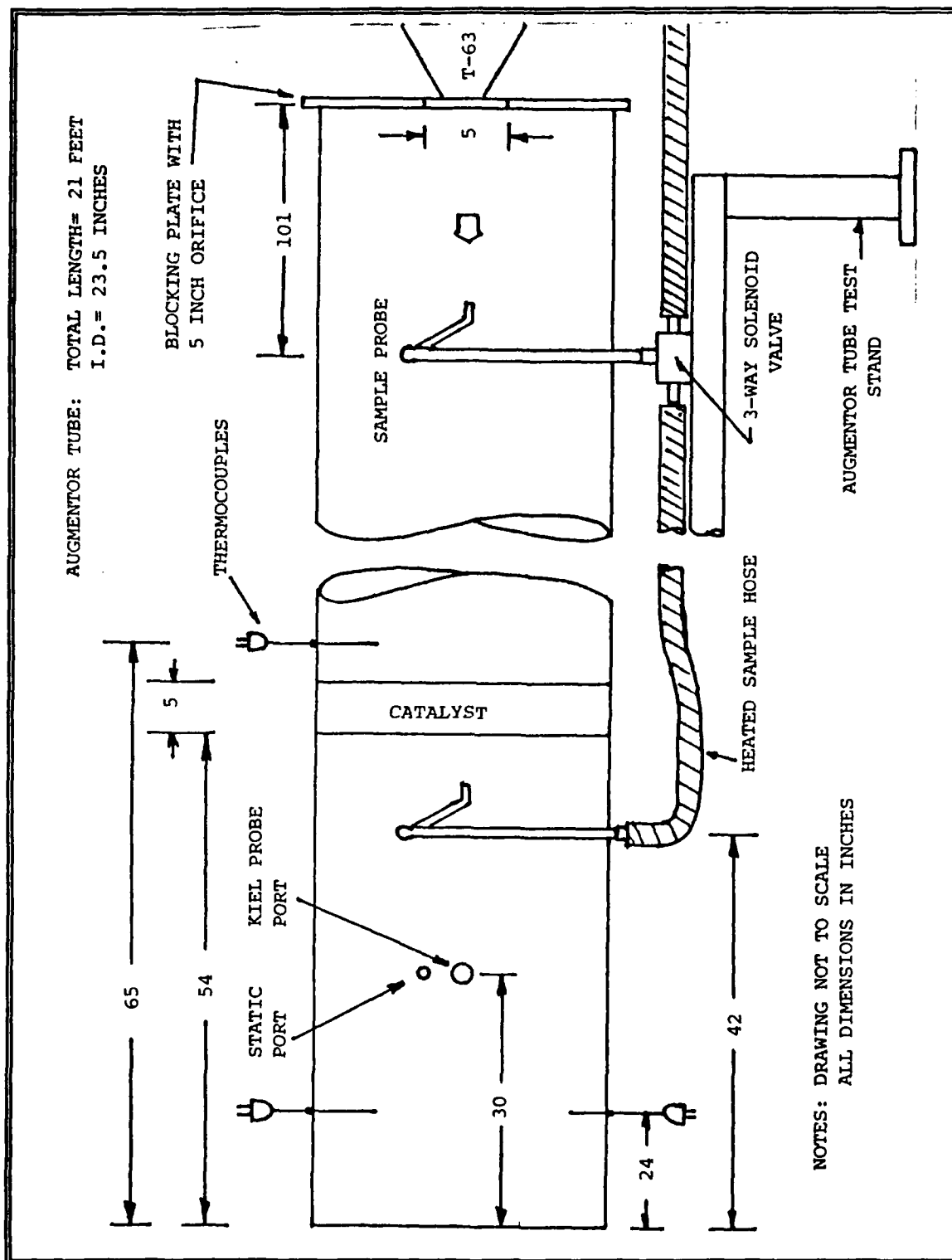
Figure 9. Schematic of Augmentor Tube and Instrumentation
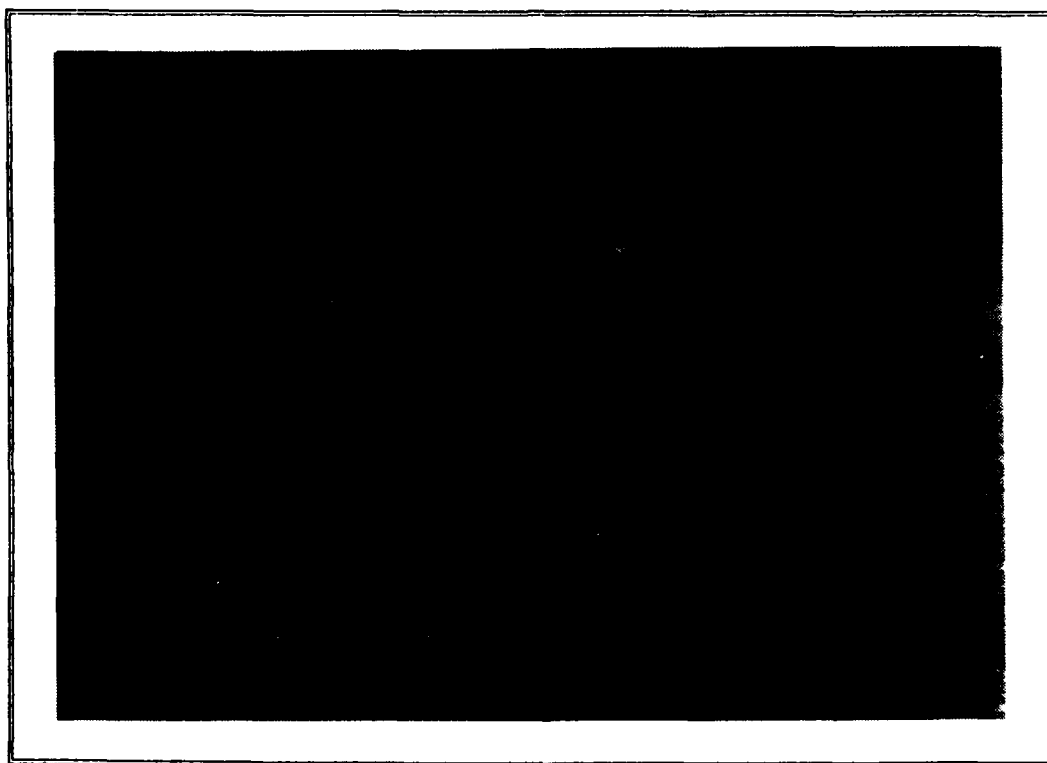
Figure 10. Photograph of Catalyst Enclosure

of 1.2 cubic feet of catalyst bed volume. The stainless steel screen mesh containing the catalytic material was made of 0.063 inch wire with a 0.187 inch mesh spacing. A removable door along the width of the basket provided for removal or replacement of catalytic material. The basket was machined so that it could be slid into the augmentor tube and secured 4.5 feet from the tube exit plane. Assuming a flow velocity of 40 feet/sec, minimum residence time through the enclosure was 0.01 seconds.

H. GAS SAMPLING AND ANALYSIS EQUIPMENT

Figure 11 shows a schematic of the sample gas flow path to the analyzers after being collected by two stainless, 1/4 inch sample probes in the augmentor tube. One sample probe was positioned upstream and one downstream of the catalyst enclosure. A three-way solenoid valve connected the heated sample line from the downstream sample probe in the augmentor tube, the upstream sample probe, and the heated sample line to the gas analyzers. The electric solenoid valve was operated from the control room via a toggle switch on the T-63 control panel. The sample lines were set to heat the sample to a temperature of 275 deg. F to prevent water condensation.
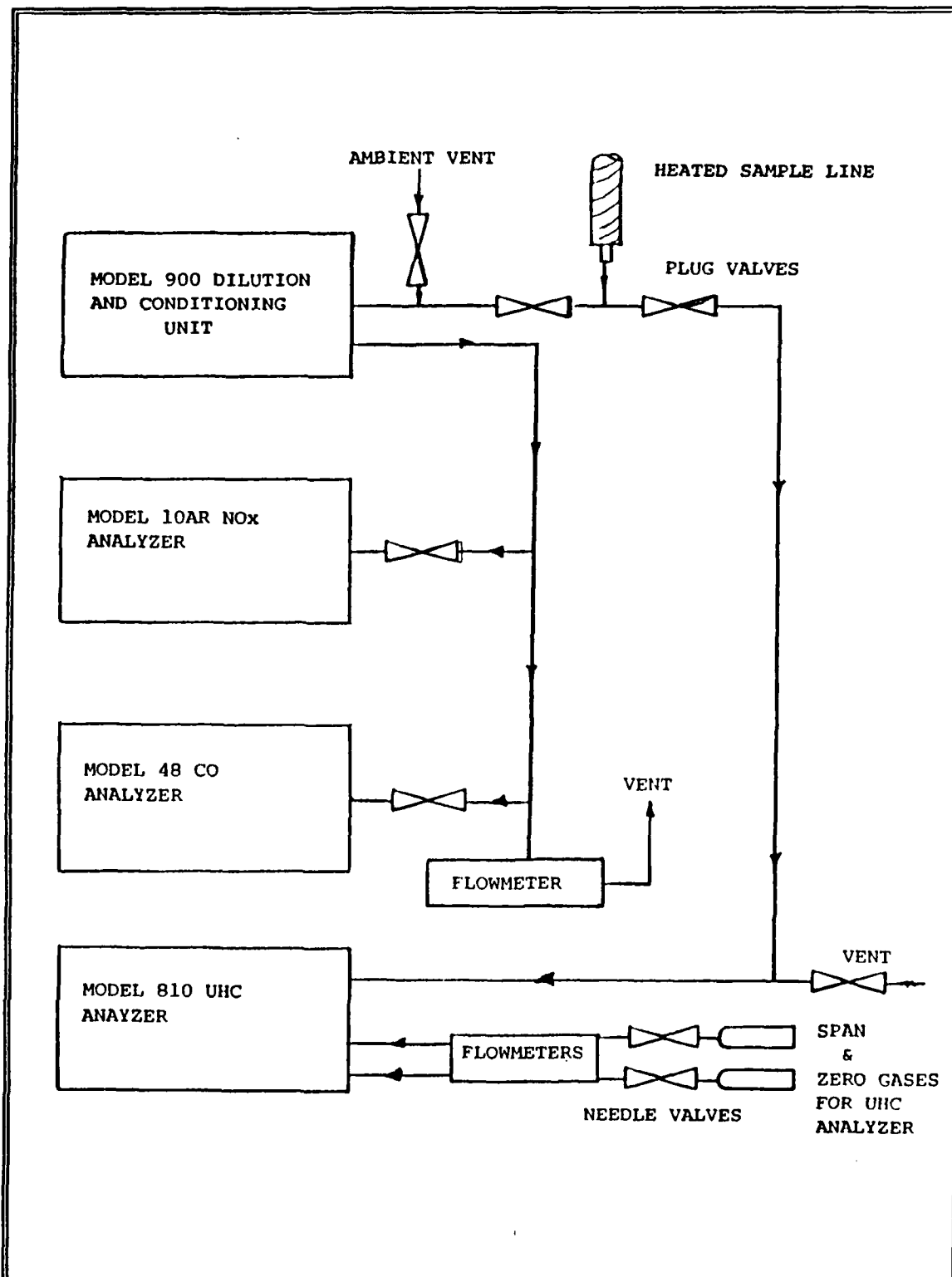
Figure 11. Schematic of Sample Gas Flow Path

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1. Model 900 Heated Sample Gas Dilution and Conditioning Unit

Sample gas was drawn at about 1.3 SCFH from the stainless sample probes in the augmentor tube through a heated sample line and introduced into a Thermal Electron Model 900 Heated Sample Gas Dilution and Conditioning Unit (Figure 12). The Model 900 blended dry dilution air at a 20:1 dilution ratio with the gas sample to reduce its dewpoint, preventing the formation of condensate at room temperature [Ref. 13]. The conditioned sample (output of the Model 900) was then delivered to the following instruments at seven SCFH and ten psig for further analysis:

1. Thermo Electron Model 10AR Chemiluminescent NO/NO_x Analyzer

2. Thermo Electron Model 48 Gas Filter Correlation (GFC) Ambient CO Analyzer.

2. Model 10AR NO/NO_x Analyzer

From the Model 900 Sample Conditioning Unit, a portion of the sample gas was provided via teflon tubing into the Thermo Electron Model 10A Rack-Mounted Chemiluminescent NO-NO_x Gas Analyzer (Figure 13) for continuous measurement of nitric oxide (NO) and nitrous oxides ($NO+NO_2$ or NO_x). The Model 10AR was capable of measurement ranges from 2.5 to 10,000 parts per million (ppm) and had a sensitivity of 0.1 ppm.
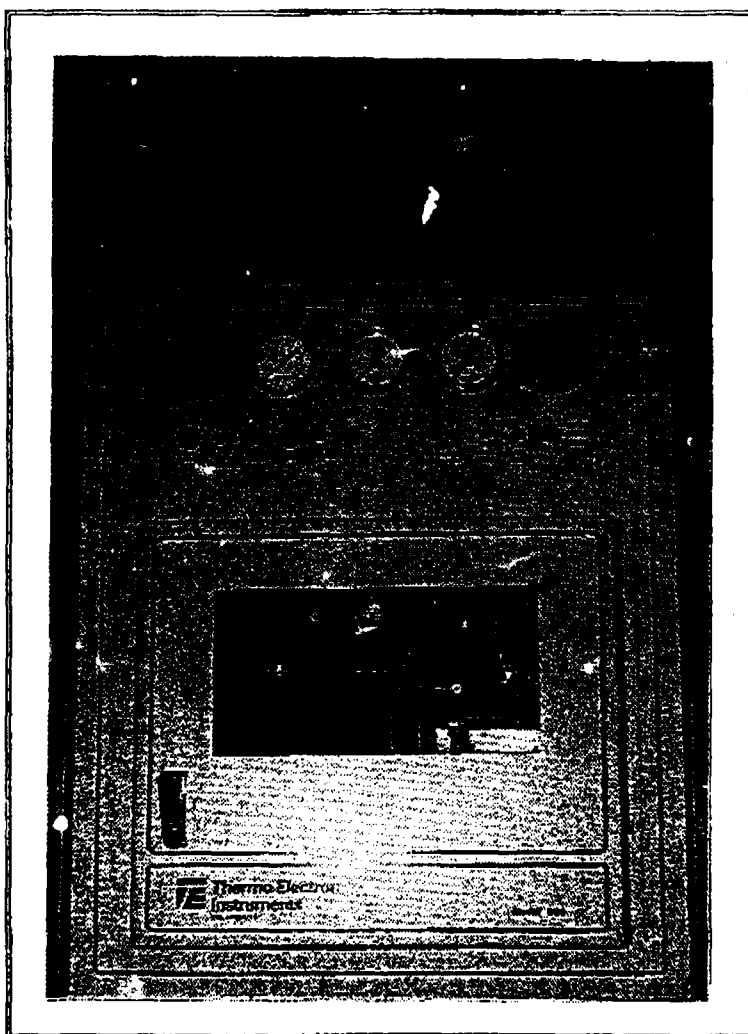
Figure 12. Photograph of Model 900 Heated
Sample Gas Dilution and Conditioning Unit
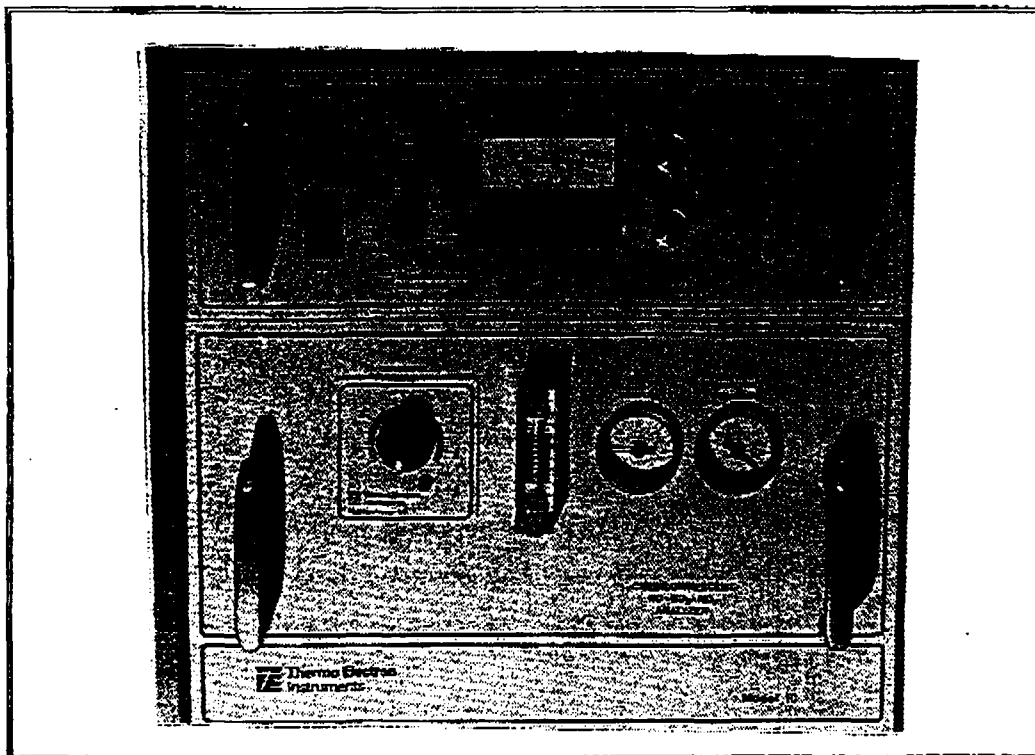
Figure 13. Photograph of Model 10AR NO-NO$_x$ Gas Analyzer

The basis of the instrument is the chemiluminescent reaction of NO and ozone (O_3) or NO+O_3 → NO_2+O_2 . Light emission results when excited NO_2 molecules revert to their ground state.

To measure NO, the gas sample was blended with ozone produced by an internal ozonator in a reaction chamber within the Model 10AR (Figure 14). The resulting chemiluminescence was measured through an optical filter by a sensitive photomultiplier (PM). The filter and PM responded to light in a narrow wavelength band unique to the chemiluminescent reaction. The output of the PM was linearly proportional to the NO concentration. [Ref. 14]

To measure NO_x, the sample gas was diverted through an NO_2-to-NO converter in which the nitrogen dioxide (NO_2) was thermally converted to nitric oxide (NO) for subsequent measurement via the chemiluminescent process. The chemiluminescent response in the reaction chamber to the converter output mixture was linearly proportional to the NO_x concentration entering the converter. [Ref. 14]

3. Model 810 Total Hydrocarbon Analyzer

A raw portion of the exhaust gas from the heated sample line was provided to the Thermo Environmental Instruments Model 810 Total Hydrocarbon Analyzer (Figure 15) at atmospheric pressure at a sampling flow rate of 2500 ml/min (5.3 SCFH). The sample gas for the Model 810 bypassed the
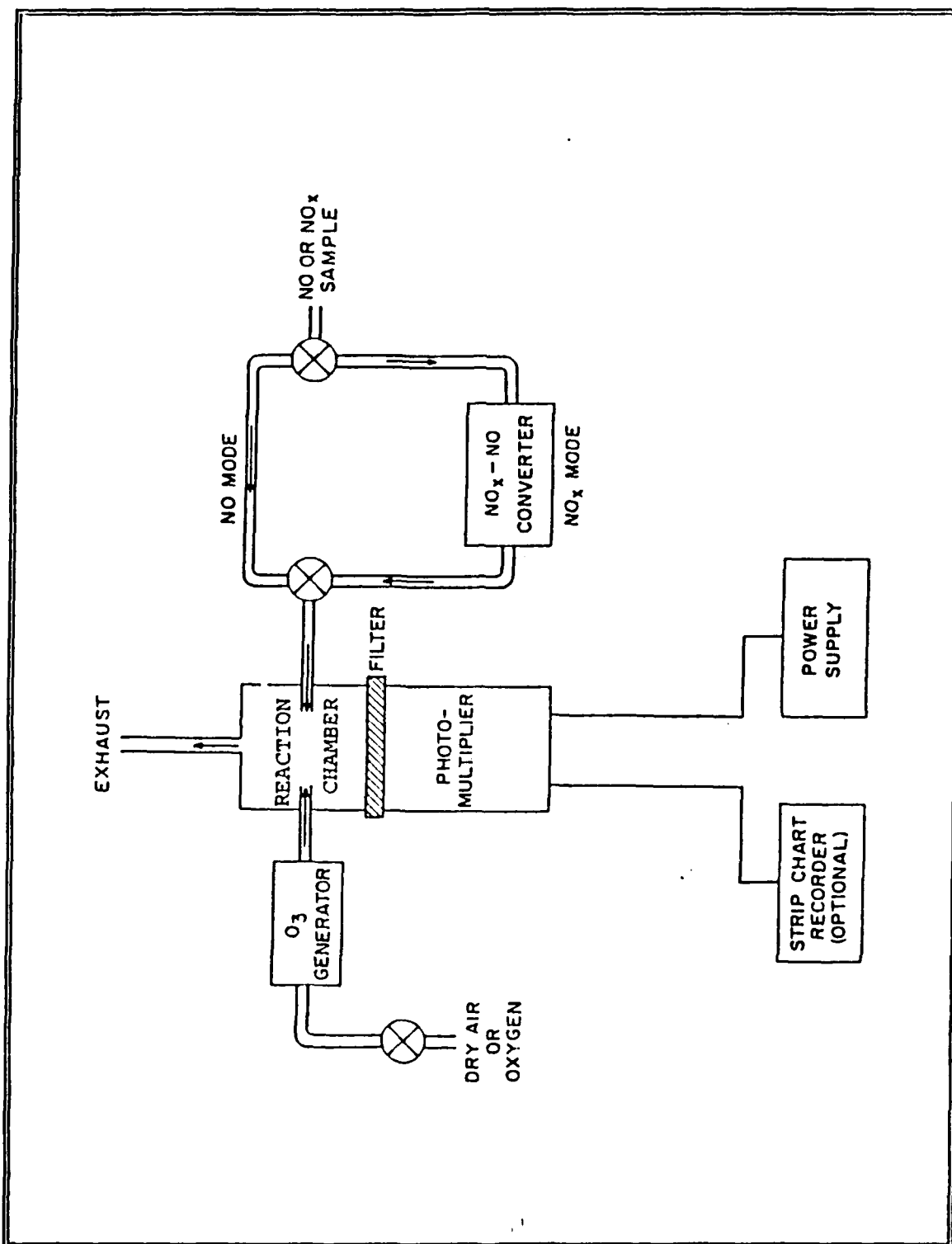
Figure 14. Conceptual Schematic of Model 10AR NO-NO$_x$ Gas Analyzer [Ref. 14]

Figure 15. Photograph of Model 810 Total Hydrocarbon
Analyzer

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Model 900 due to the high dilution ratio of the Model 900 and the low concentrations of hydrocarbons expected in the exhaust. The Model 810 measured hydrocarbon concentration ranges of 0.1 to 10,000 ppm with an accuracy of 0.1 ppm utilizing an internal hydrogen flame ionization detector. The detector operated by ionizing volatile organic compounds using a hydrogen flame. The gas sample was mixed with hydrogen prior to the flame. External combustion air was provided for combustion of the sample in the flame. Normally, sample flow and hydrogen flow were equal and combustion air was five to ten times greater. Upon combustion, the hydrogen flame burned the organic compounds in the sample to generate carbon dioxide and water. Carbon ions were also formed in the process. This process occurred in an electrical field between two electrodes, one near the hydrogen flame and one around the flame or a collector electrode. The potential difference between the two electrodes caused movement of ions to one or the other electrode. A small ion current flowed, was amplified, and provided to the microprocessor system of the Model 810. [Ref. 15]

The Model 810 required calibration with a known span gas (known concentration of hydrocarbons), zero air (less than 0.1 ppm concentration of hydrocarbons), combustion air or oxygen, and hydrogen.

4. Model 48 GFC Ambient CO Analyzer

Another small portion of the conditioned sample gas from the Model 900 Conditioning Unit was drawn off and introduced into the Thermo Electron Model 48 Gas Filter Correlation (GFC) Carbon Monoxide (CO) Ambient Analyzer (Figures 16 and 17) at a flow rate of about one liter per minute at atmospheric pressure. The Model 48 was capable of measuring CO concentrations from 0.1 to 1000 ppm with an accuracy of 0.1 ppm utilizing non-dispersive infrared absorption techniques. Since infrared absorption is a non-linear measurement technique, the Model 48 transformed the basic analyzer signal into a linear output. This was done internally by the Model 48 by storing the calibration curves in computer memory and subsequently using the curves to accurately linearize the instrument output over a desired range. An internal temperature and pressure transducer provided outputs into a microcomputer to make corrections to instrument output, resulting in CO concentration measurements which were unaffected by changes in sample gas pressure and temperature.

The sample gas CO concentration in the Model 48 was determined using an internal Gas Filter Correlation Spectrometer. GFC spectrometry is based upon the comparison of the detailed structure of the infrared absorption spectrum of the measured gas to that of other gases also present in the
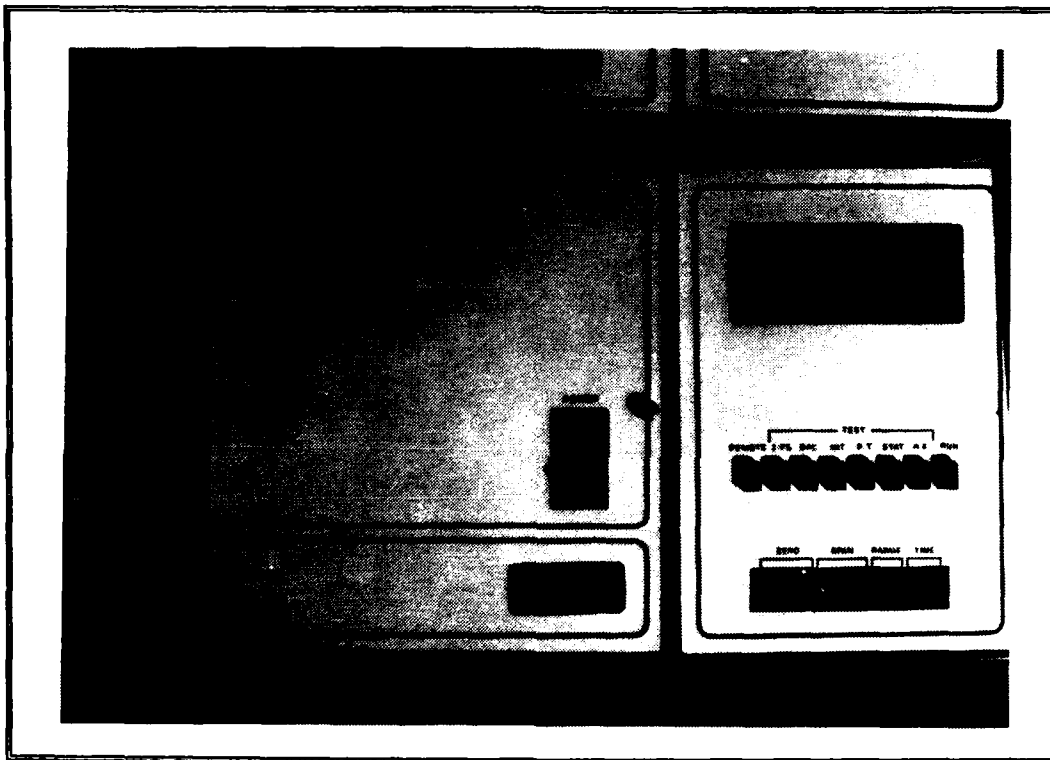
Figure 16. Photograph of Model 48 GFC CO Analyzer
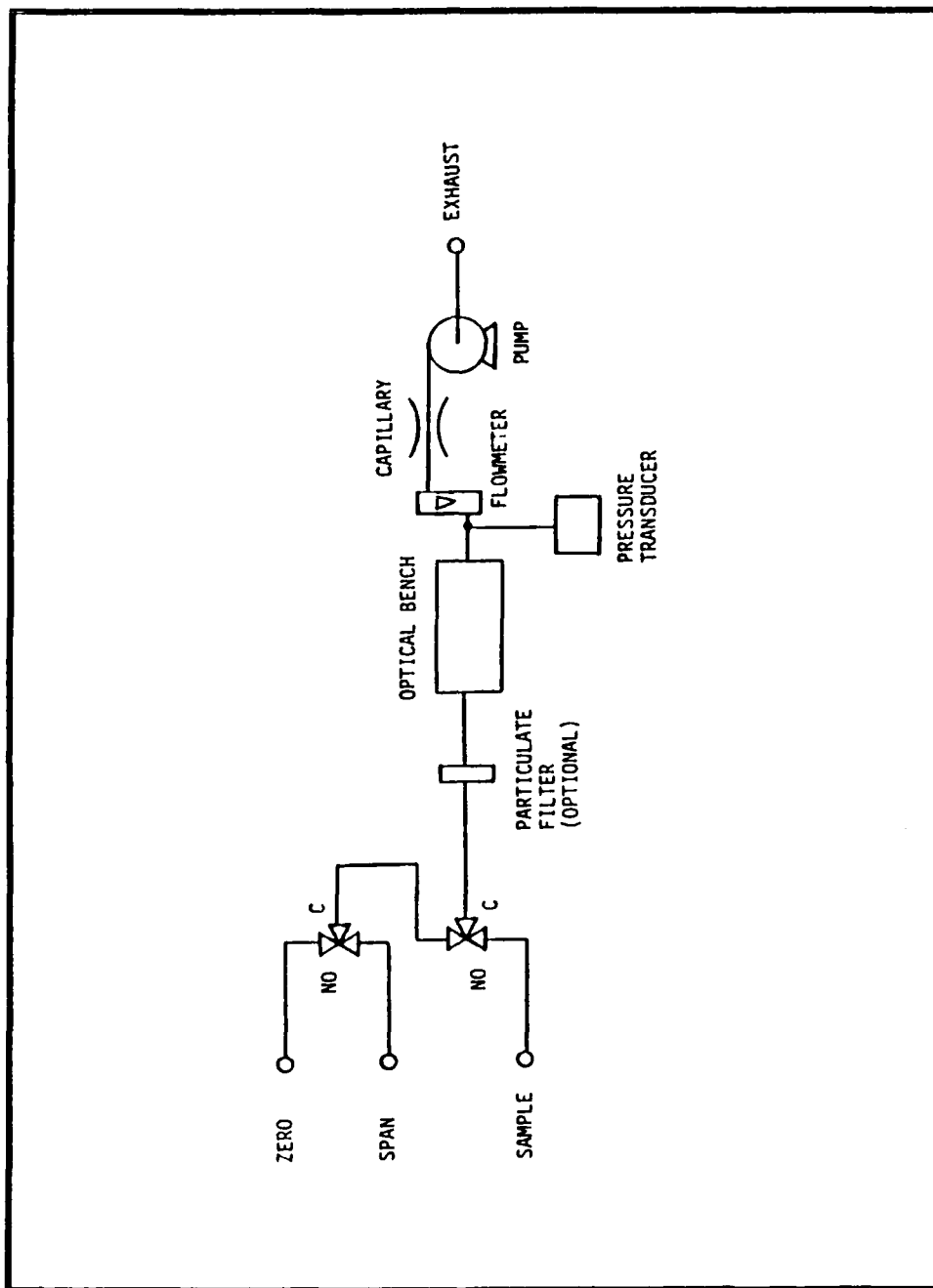
Figure 17. Flow Schematic of Model 48 CO Analyzer
[Ref. 16]

sample. The technique is implemented by using an input of a high concentration of CO (known span gas) as a filter for the infrared radiation transmitted through the analyzer (GFC). The basic components of the GFC CO spectrometer are shown in Figure 18. Radiation from an IR source is chopped and then passed through a gas filter alternating between CO and nitrogen due to rotation of the filter wheel. The radiation then passes through a narrow bandpass interference filter and enters a multiple optical pass cell where absorption by the sample gas occurs. The IR radiation then exits the sample cell and falls on the IR detector. [Ref. 16]

The CO gas filter acts to produce a reference beam which cannot be further attenuated by CO in the sample cell. The nitrogen side of the filter wheel is transparent to the IR radiation and produces a measure beam which is absorbed by CO in the cell. The chopped detector signal is modulated by the alternation between the two gas filters with an amplitude related to the concentration of CO in the sample cell. Other gases do not cause modulation of the detector signal since they absorb the reference and measure beams equally. This means that the GFC system responds specifically to carbon monoxide. The sensitivity of the Model 48 is increased to 0.1 ppm with a lower detectable limit of 0.02 ppm by using multiple pass optics in the sample cell leading to a large path length or improved sensitivity. [Ref. 16]
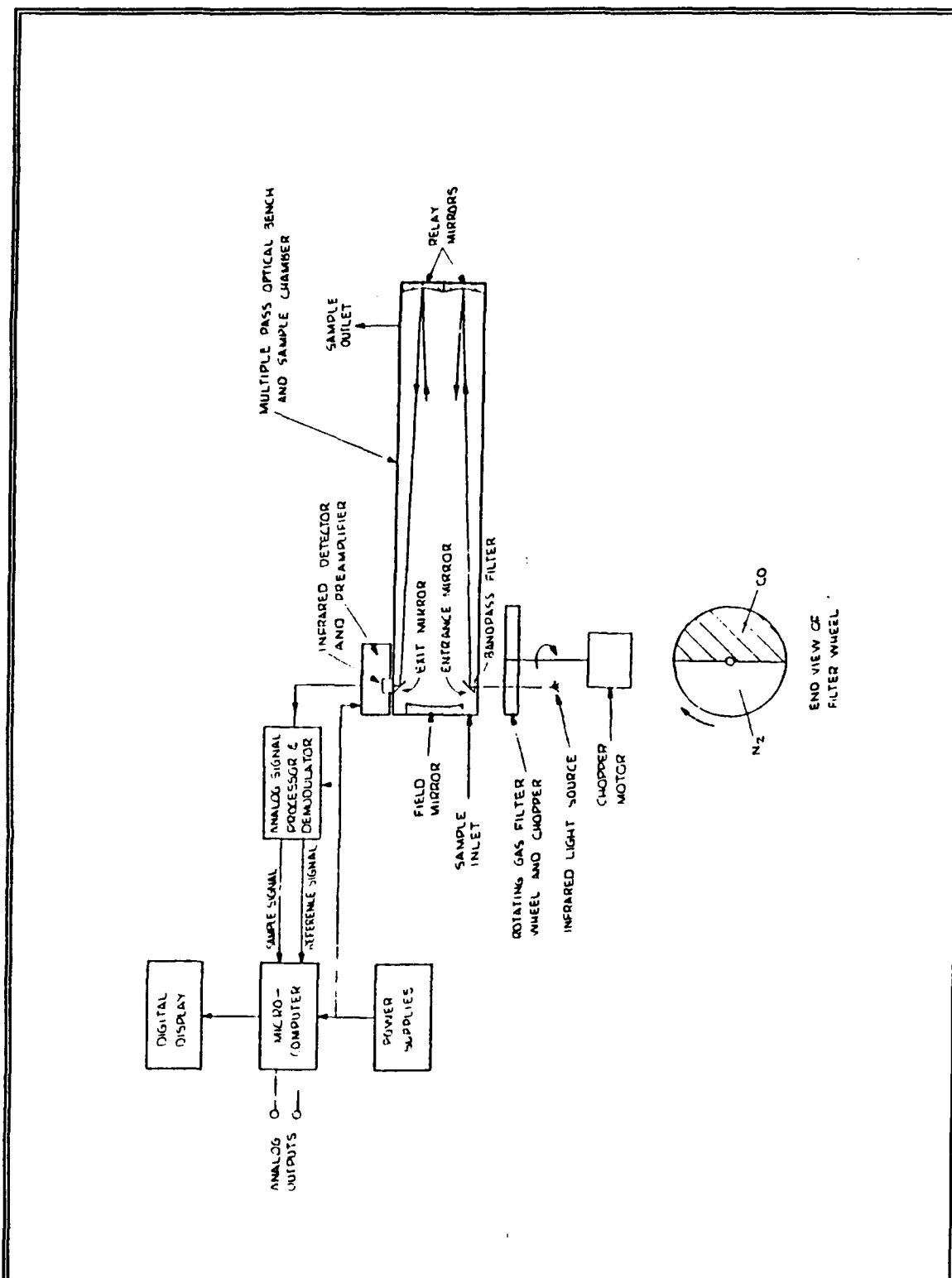
Figure 18. Diagram of Model 48 GFC Spectrometer   [Ref. 16]

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I. CONTROL ROOM

A main control room and associated control panels were located adjacent to the test cell in the NPS Combustion Lab, Building 217, NPS Annex. The control room provided a secure and quiet space to control and visually observe the experiment as well as house the sample gas conditioning unit, gas analyzers, and data acquisition system. Figure 19 provides a photograph of the layout of the control panel including controls for:

1. main air (red guarded)

2. T-63 air heater torch and gases (red guarded)

3. T-63 combustor ignitor

4. T-63 combustor fuel system and tank vent

5. fuel tank pressure and hand loader.

Adjacent to the panel was a digital readout of the JP fuel flowrate in gallons per minute (GPM) as well as a jet exhaust temperature readout for safety backup. The main air pressure gauge and hand loader were located on the solid fuel ramjet (SFRJ) air heater console near the T-63 combustor control panel.

J. DATA ACQUISITION AND REDUCTION SYSTEM

A Hewlett-Packard HP-3054A automatic data acquisition/control system located in the control room

38
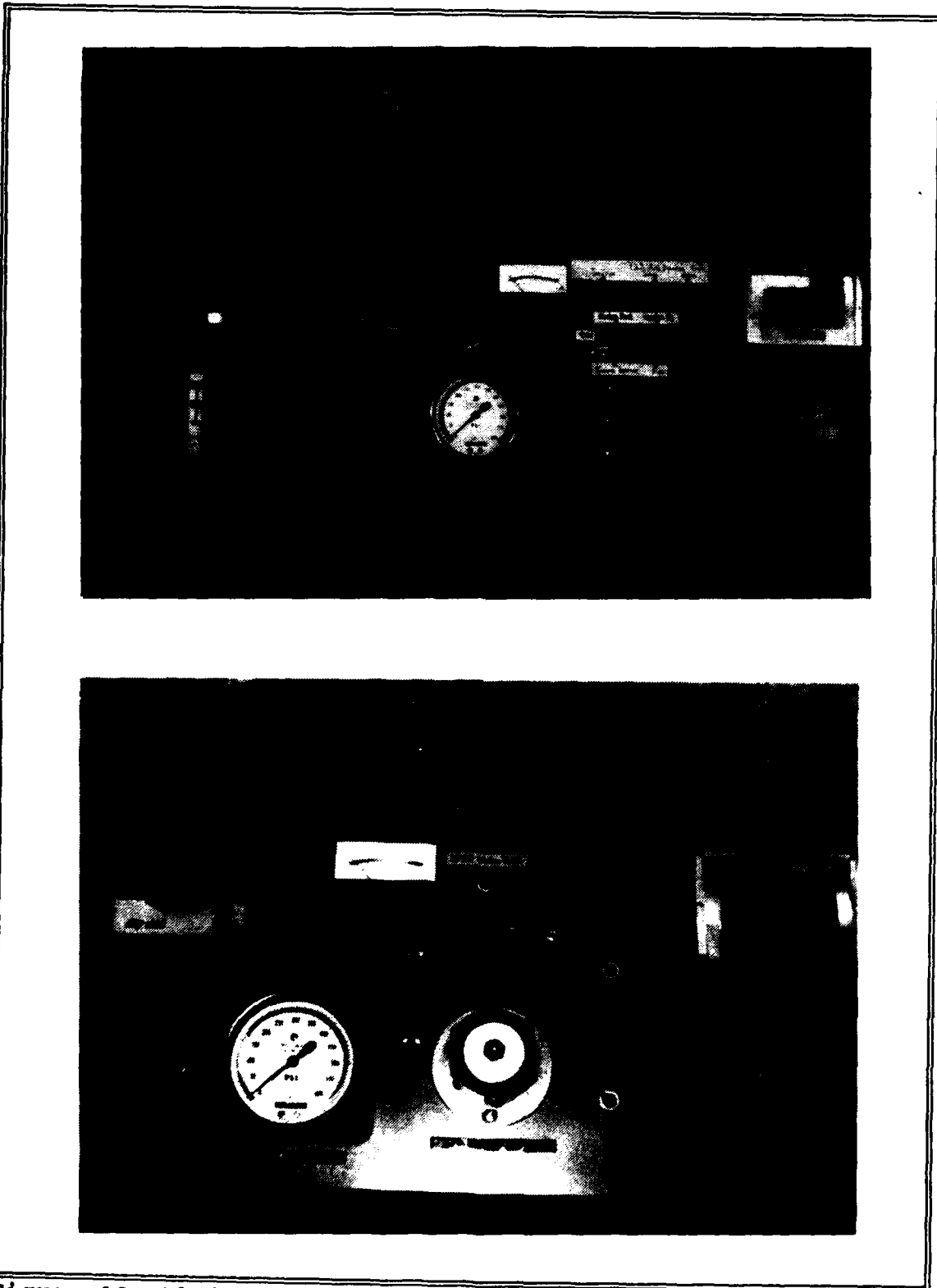
Figure 19. Photograph of T-63 Control Panels

provided test data acquisition, reduction, and system control for the experiment. The system included a HP-3497A data acquisition and control unit (DACU), a HP 3456A digital voltmeter, and a HP-9836S microcomputer with a HP-9153C hard disk drive (Figure 20). The test controlling software program (Appendix A) was written in HP Basic 5.1 and loaded from the HP-9153C hard disk for each test run. The software was programed for transducer calibration, setup of gaseous flows, data acquisition and reduction for each hot data run.
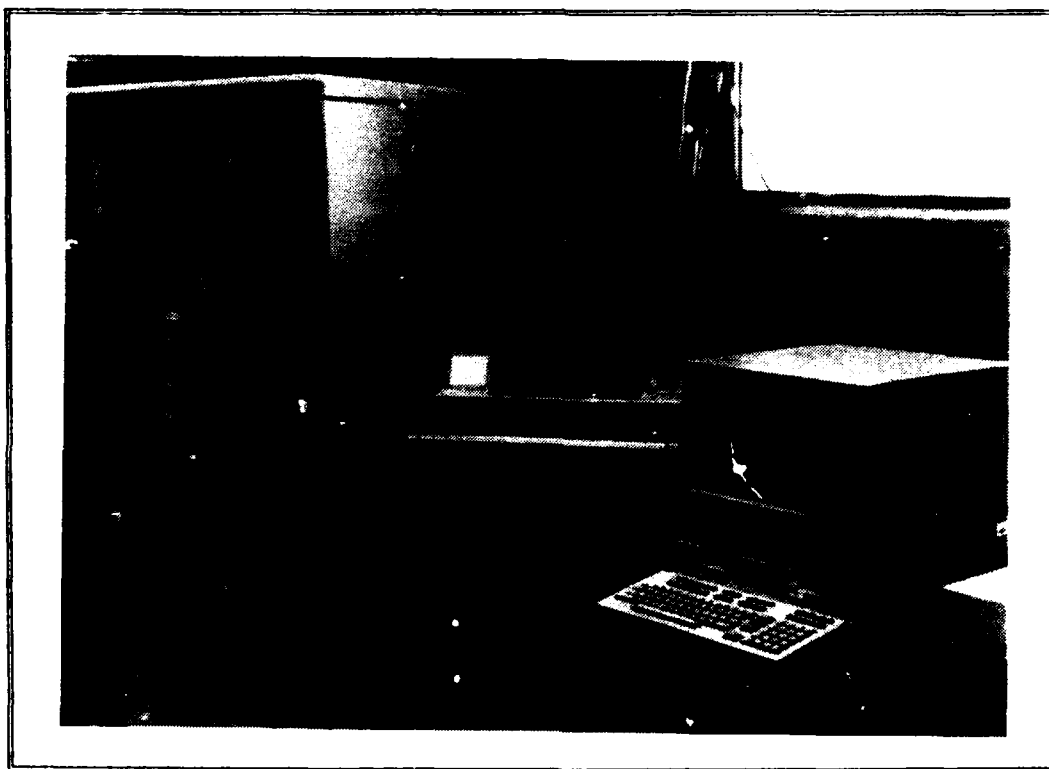
Figure 20. Photograph of H-P Data Acquisition and Control
System

III. EXPERIMENTAL PROCEDURE

Prior to any data runs, the T-63 combustor, augmentor tube, traversing probe system, gas analyzers, and associated software were checked and tested to ensure the equipment operated satisfactorily after installation.

The sample gas analyzers were calibrated with their respective zero and span gases. In accordance with Reference 14, the Model 10AR NO_x analyzer was calibrated with a zero gas of less than 0.1 ppm NO and a span gas containing 220 ppm of NO in nitrogen. The Model 48 CO analyzer was calibrated with a zero gas of less than 0.1 ppm CO and a 104 ppm CO span gas. The NO_x and CO analyzer calibration gases were routed through the Model 900 Dilution and Conditioning unit prior to entering their respective analyzer for calibration, since the actual sample gas would also be conditioned through the Model 900. Since the Model 900 diluted any sample input at a 20:1 ratio, all sample gas readings from the Model 48 and Model 10AR during a data run were multiplied by 20 to obtain the actual specie concentration in ppm.

The Model 810 Total Hydrocarbon analyzer was calibrated with a zero gas of less than 0.1 ppm of methane (CH_4) in air and a span gas of 50 ppm methane in air in accordance with Reference 15. Since the Model 810 automatically initiated a calibration sequence upon start and at prescribed intervals,

the zero and span gases were permanently plumbed to the unit. Before connecting them to the Model 810, the zero and span gas flow rates were set externally (to 0.53 SCFH) using two flow meters and needle valves. Due to the calibration requirements, the T-63 exhaust sample gas was introduced directly into the Model 810, bypassing the Model 900. All analyzers and the Model 900 were energized one hour prior to a hot data run to ensure proper warmup and operation. This normally allowed enough time for the Model 900 chamber temperature to reach 180 degrees F as required.

All pressure transducers required calibration prior to data collection. The computer program "T63NOX" (Appendix A) was used to complete the calibration. New calibration constants and zero values were obtained and entered into the program for data reduction.

The Kiel total pressure probe and static pressure port transducers were calibrated with a manometer and strip chart recorder in the control room. The calibration resulted in a constant of 10 mV per 0.58 cm of water for the static port and 10 mV per 0.53 cm of water for the Kiel total pressure probe.

With the probes, transducers, and analyzers set, the Run Checklist (Appendix B) was completed and the various flow rates (main air, air heater fuel, heater oxygen) were set in accordance with the "T63NOX" computer program on the H-P microcomputer. On cue from the computer, the air heater and

combustor were ignited from the control panel in the control room. The combustor was operated at normal engine operating fuel to air ratios (f = 0.017-0.019). The Kiel probe traversed across the augmentor tube exit plane and gas samples were taken from both collection probes in the augmentor tube and processed by the gas analyzers.

Originally, four hot data runs were to be completed. Two runs each were to be made both with and without a catalytic bed inserted in the augmentor tube; one of these runs without the vitiated air heater activated. The runs without the catalyst were made to establish the base concentration of NO_x, CO, and UHC and to determine the augmentation ratios from the average temperatures and velocities across the tube exit plane. CO and UHC levels were measured since it had been shown (Ref. 4) that their presence can significantly change the effectiveness of a catalyst for NO_x reduction. For example, NO can be reduced by CO using a rhodium catalyst to produce CO_2 and N_2. The other two data runs were to be made with an iron oxide catalyst inserted in the augmentor tube following the work of Reference 6. When the iron oxide catalyst became unavailable (due to the supplier deciding that it would not work adequately in the augmentor tube environment), a vermiculite catalyst (an aluminum-iron-magnesium silicate) was ordered to evaluate the recent results of Reference 7 within the augmentor tube environment. This

material was not delivered in time for evaluation. Course perlite (an inexpensive, amorphous, sodium-potassium-aluminum silicate) was then obtained for testing (also based on the recent results of Reference 7), but the grain size proved to be too small for the catalytic bed screen mesh. A finer mesh screen was therefore attached to both sides of the coarse wire basket. A fourth data run was then completed with the catalyst, but without activating the vitiated air heater. The run was made to evaluate the effectiveness of the perlite catalyst for NO_x reduction and to determine the effect of the catalytic bed on the augmentation ratio.

IV. RESULTS AND DISCUSSION

A summary of the results of the four data runs is presented below in Table II. A more comprehensive data output for each run appears in Appendix C.

Table II. SUMMARY OF RESULTS

MEASUREMENT	RUN NUMBER			
	1	2	3	4
air heater used	no	yes	no	no
catalyst installed	no	no	no	yes
$\dot{m}_a$ (1bm/sec)	1.92	1.95	1.83	1.91
f	0.017	0.009	0.019	0.018
V_{avg} (ft/sec)	41.5	33.0	36.2	*
AR	1.17	0.69	0.78	negl.
T_{augup} (deg. R)	903	899	997	989+
T_{exl} (deg. R)	1550	1374	1693	1555+
NO_x (ppm)	26	14	30	50/18
CO (ppm)	360	82	220	520/220
UHC (ppm)	135	250	58	38/18

Notes: For Run #4:
       * unable to calculate
      + data taken early in test
      gas concentrations :
      upstream/downstream of catalytic bed

It is evident from the data of runs 1, 2, and 3 that as the combustor temperature increased, exhaust NO_x levels also increased and UHC concentrations decreased as expected for gas turbine combustors and confirming the trend found in Reference 7. CO levels were quite high for the first three runs except for run #2, which is suspect. As the combustion temperature and augmentation ratio decreased, CO levels should have increased. This behavior was not observed and could have been the result of either the low combustor flow rate or improper functioning of the CO analyzer. Overall CO and UHC levels were somewhat higher than reported in Reference 7. Differences could have been attributed to defined power settings and combustion temperatures in the engine data of Reference 7. Additionally, the Model 810 UHC analyzer used in the tests had experienced calibration problems during the experiments.

The average velocities near the augmentor tube exit (18.5 feet downstream of combustor exhaust) for the first three runs were fairly close in value. The velocity and temperature profiles were fairly uniform with a relatively constant velocity (constant stagnation pressure) in the center of the flow as expected. The flow did exhibit slightly greater velocities near the wall of the tube, possibly the result of the mixing process between the engine exhaust and augmentor air in the large diameter augmentor tube. The lower velocity

and augmentation ratio during run #2 (vitiated air heater activated) was a result of an initial combustor overtemperature condition at the normal operating fuel to air ratio upon ignition. This required a reduced fuel-to-air ratio to be used. The resulting correction was too severe and produced a much lower combustor exhaust temperature.

Run #4 was accomplished with a perlite catalytic bed inserted 4.5 feet from the tube exit. Temperatures entering the bed were initially 989 deg. R (529 deg. F). Due to the large pressure drop caused by the catalytic bed obstructing the flow through the tube, the augmentation ratio was greatly reduced, resulting in the tube temperature being increased substantially as the run progressed. The velocity profile downstream of the catalyst exhibited areas of flow reversal and substantially higher velocities near the wall due to an inexact seal between the wall and catalyst enclosure. Additionally, fine particles of perlite were inducted into the Kiel probe head, hampering efforts to obtain a reliable average exit velocity. Based upon the measured data and the observed very high augmentor tube wall temperature, the augmentation ratio was known to be very small.

The perlite catalytic bed did provide for a 64% reduction in NO_x which was on the order found in Reference 7 (for a subscale test) for a perlite + $MgSO_4$ bed at 860 deg. R. The long residence times (probably on the order of 0.01-0.03

seconds), large exposed surface area of the catalyst particles, and higher bed temperatures probably contributed to the apparent success of the perlite catalyst. The catalyst also appeared to cause a decrease in CO and UHC. This may be the result of the oxidation of CO over the catalyst.

It was apparent from these initial tests that the catalytic reduction of NO_x in test augmentor tubes is practical. However, to not adversely affect the augmentor flow rate, the catalysts will have to be distributed in such a manner to reduce flow rate resistance. Two such methods are; (1) placing the catalyst material in tubular structures (honeycombs) and, (2) treating only the central region of the flow where the NO_x levels are at their highest values.

In this initial investigation, the augmentor tube diameter was made large and the augmentor inlet orifice small in order to provide low velocities (30-40 ft/sec) through the catalytic bed. This was done to determine the effectiveness of the catalyst under the most ideal conditions and with a minimum of catalytic material. Augmentation ratios as high as five and velocities as high as 1000 ft/sec are not uncommon in full-scale test cells. Once the most effective catalyst is found, it must be evaluated over the full range of velocities and temperatures encountered in the test cell environment.

Another issue which must be addressed is the impact of soot (which can accumulate with run time) on the effectiveness

of the catalyst.

V. CONCLUSIONS AND RECOMMENDATIONS

Most of the initial objectives for this investigation were met. The T-63 combustor, associated instrumentation, and software operated satisfactorily. A test stand for the augmentor tube was designed and built. The sample gas analyzers were set up and calibrated and a sample flow system was constructed for transporting the exhaust sample from the probes in the augmentor tube to the analyzers. A long response time was noticed during the tests due to the long sample hose lengths required to transport the sample to the analyzers and small orifice size in the three-way solenoid valve at the augmentor tube stand. Movement of the analyzers to the test cell, increasing the orifice of the solenoid valve, and increasing the sample probe size to 3/8 inch stainless steel could minimize sample travel time and distance to the analyzers and suction resistance in the tubing.

The general velocity and temperature profiles across the augmentor tube were determined to be relatively constant and used to obtain augmentation ratios when practical. The perlite catalytic bed resulted in a 64% NO_x removal. This supports a conclusion that perlite is a viable, inexpensive catalyst material which could be used in the test cell environment. The large pressure drop observed across the

catalytic bed, however, makes the current configuration impractical. Alternative configurations might include:

1. For total exhaust flow treatment, a honeycombed catalyst enclosure could be manufactured which would allow a larger flow velocity through the bed and lower pressure drop. Systems of this type are discussed in Reference 6.

2. Construction of an extractive system involving placement of a smaller, coarse catalytic bed centered along the augmentor tube center axis where the greater concentration of NO_x might be expected. To construct this configuration, velocity, temperature, and NO_x concentration profiles would have to be found along the augmentor tube to optimize exact catalytic bed placement and NO_x removal.

Since time constraints precluded a more in-depth investigation, future efforts, utilizing the current apparatus and various species of catalytic material (Fe_2O_3 and vermiculite when available), should concentrate on varying the augmentation ratio and fuel to air ratio and measuring NO_x, CO, and UHC levels across the catalyst. The effects of these variables in consonance with ammonia or cyanuric acid addition techniques (as discussed in References 4, 5, and 6) on the effectiveness of the catalytic process should be investigated.

In addition, the effects of sooting and much higher augmentor tube velocities and augmentation ratios must be evaluated before a practical solution can be attained.

APPENDIX A

HP BASIC "T63NOX" COMPUTER PROGRAM

```
10    ! T63 VERSION 9, JAN 1990
20    PRINTER IS 1
30    ! T63 COMBUSTOR DATA ACQUISITION AND REDUCTION PROGRAM
40    ! THIS PROGRAM IS DIVIDED INTO FIVE PARTS:
50    !       (1) VARIABLE DEFINITIONS AND NOMENCLATURE
60    !       (2) TRANSDUCER CALIBRATIONS
70    !       (3) FLOW CHECKS AND NOZZLE CALCULATIONS
80    !       (4) THE TEST SEQUENCE AND DATA COLLECTION
90    !       (5) POST-RUN OPERATIONS, DATA REDUCTION AND SHUTDOWN
100   !***********************************************************************
110   !(1) VARIABLE DEFINITIONS AND NOMENCLATURE
120   !***********************************************************************
130   ! SYMBOL              DEFINITION
140   ! A                   ANALOG CHANNEL NUMBER
150   ! Aair                THROAT AREA,AIR FLOW SONIC CHOKE, SQ. IN.
160   ! Ahf                 THROAT AREA,HEATER FUEL SONIC CHOKE, SQ.IN.
170   ! Aho                 THROAT AREA,HEATER OXYGEN SONIC CHOKE, SQ.IN.
180   ! BFair               BYPASS AIR FLOWRATE
190   ! Cdair               DISCHARGE COEFFICIENT, AIR SONIC CHOKE
200   ! Cdhf                DISCHARGE COEFFICIENT, HEATER  FUEL SONIC CHOKE
210   ! Cdho                DISCHARGE COEFFICIENT, HEATER O2 SONIC CHOKE
220   ! Dairchoke           AIR SONIC CHOKE DIAMETER
230   ! Dbpchoke            BYPASS AIR SONIC CHOKE DIAMETER
240   ! Date$               Test Date  Mo-Day-Yr
250   ! Dhfchoke            AIR HEATER FUEL SONIC CHOKE DIAMETER
260   ! Dhochoke            AIR HEATER OXYGEN SONIC CHOKE DIAMETER
270   ! Fuelid$             FUEL IDENTIFICATION
280   ! Gc                  32.174
290   Gc=32.174
300   ! Heaterfuel          HEATER FUEL IDENTIFICATION
310   !
320   ! Kmair               AIR SONIC CHOKE FLOW RATE CONSTANT
330   ! Kmfuel              FUEL FLOW METER RATE CONSTANT (GPM/VOLT
340   ! Kmhf                HEATER FUEL SONIC CHOKE FLOW RATE CONSTANT
350   ! Kmho                HEATER O2 SONIC CHOKE FLOW RATE CONSTANT
360   ! Kp                  PRESSURE TRANSDUCERS CONSTANT (PSI/VOLT)
370   ! Mair                AIR FLOW RATE, LBM/SEC
380   ! Maird               DESIRED AIR FLOW RATE, LBM/SEC
390   ! Mfuel               FUEL FLOW RATE, GPM
400   ! Mfueld              DESIRED FUEL FLOW RATE, GPM
410   ! Mhf                 HEATER FUEL FLOW RATE, LBM/SEC
420   ! Mhfd                DESIRED HEATER FUEL FLOW RATE LBM/SEC
430   ! Mho                 HEATER OXYGEN FLOW RATE, LBM/SEC
440   ! Mhod                DESIRED HEATER OXYGEN FLOW RATE, LBM/SEC
450   ! Pa                  PRESSURE, AIR SONIC CHOKE, PSIA
460   ! Pbpa                PRESSURE, BYPASS AIR SONIC CHOKE, PSIA
470   ! Pbar                BAROMETRIC PRESSURE, PSIA
480   ! Pc                  PRESSURE, COMBUSTION CHAMBER, PSIA
490   ! Phf                 PRESSURE, HEATER FUEL SONIC CHOKE, PSIA
500   ! Pho                 PRESSURE, HEATER OXYGEN SONIC CHOKE, PSIA
510   ! Ta                  TEMPERATURE, AIR SONIC CHOKE, R
520   ! Tbpa                TEMPERATURE, BYPASS AIR SONIC CHOKE, R
530   ! Tauaup              TEMPERATURE, AUGMENTOR TUBE UPSTREAM CATALYST, R
```

```
540  !  Taugd1           TEMPERATURE, AUGMENTOR TUBE DOWNSTREAM CATALYST, R
550  !  Testno$          TEST I.D NO.
560  !  Thf              TEMPERATURE, HEATER FUEL SONIC CHOKE, R
570  !  Tho              TEMPERATURE, HEATER O2 SONIC CHOKE, R
580  !  Tcin             TEMPERATURE, COMBUSTOR AIR INLET (HEATER OUTLET), R
590  !  Tcind            TEMPERATURE, DESIRED COMBUSTOR AIR INLET, R
600  !  Tex1             TEMPERATURE, COMBUSTOR EXHAUST UPSTREAM OF QUENCH, R
610  !  Tex2             TEMPERATURE, COMBUSTOR EXHAUST DOWNSTREAM OF QUENCH,R
620  BEEP 1000,.1
630  PRINT USING "@"
640  PRINT USING "6/"
650  PRINT " T63 DATA ACQUISITION "
660  PRINT USING "5/"
670  PRINT "TURN THE PRINTER ON LINE"
680  CLEAR 709
690  CLEAR 722
700  ! THE RECORDED VARIABLES (VOLTAGES) AND LOCATIONS ARE:
710  ! (NOTE: THE MAXIMUM ALLOWABLE VOLTAGE INTO THE SYSTEM IS 1.2 VOLTS)
720  !
730  ! VARIABLE                          3497 DACU SCANNER NUMBER 0__
740  !
750  ! Pa                                24
760  ! Pbpa                              24
770  ! Pc                                23
780  ! Mfuel                             25
790  ! Phf                               22
800  ! Pho                               21
810  ! Ta                                60
820  ! Tcin (inlet air)                  61
830  ! Tex1 (upstream of quench)         62
840  ! Tex2 (downstream of quench)       63
850  ! Tho                               64
860  ! Thf                               65
870  ! Taugun                            66
880  ! Taugd1                            67
890  ! Taugd2                            68
900  !ALL FLOW RATES ARE CALCULATED USING THE ONE-DIMENSIONAL, ISENTROPIC
910  !FLOW EXPRESSIONS WITH FIXED PROPERTIES. SMALL SONIC NOZZLES HAVE
920  !MEASURED DISCHARGE COEFFICIENTS. THE AIR FLOW NOZZLE USES AN ASSUMED
930  !DISCHARGE COEFFICIENT (Cd) OF 0.97.
940  !
950  !M (LBM/SEC)=Cd*P*A*Km/T^.5
960  !
970  !Km IS THE GAS-DEPENDENT SONIC CHOKE FLOW RATE CONSTANT
980  !
990  !Km=SQR((Gamma*Gc/R)*(2/(Gamma+1))^((Gamma+1)/(Gamma-1)))
1000 !
1010 ! APPROPRIATE CONSTANTS ARE:
1020 !
1030 ! GAS       MOLECULAR WT.   GAS CONST.    CP      GAMMA     Km
1040 !
1050 ! AIR       28.97           53.3          .240    1.40      .5320
1060 ! O2        32.0            48.3          .217    1.40      .5589
1070 ! CH4       16.03           96.4          .593    1.32      .3876
1080 ! N2        28.01           55.16         .248    1.40      .5229
1090 ! H2        2.016           766.5         3.419   1.405     .1405
1100 !
1110 Gammaair=1.40
1120 Gammaox=1.40
1130 Gammahf=1.405
1140 Kmair=.5320
1150 Kmho=.5589
```

```
1160  Kmhf=.1405
1170  Rair=53.3
1180  Rho=48.3
1190  Rhf=766.5
1200  Dairchoke=.42
1210  Dbpchoke=.239
1?    Dhochoke=.0780
12.0  Dhfchoke=.040
1240  Maird=1.9
1250  Mbpaird=.59
1260  Mfveld=.33
1270  Mhfd=.00285
1280  Mhod=.0228
1290  PRINT USING "6/"
1300  INPUT "Input the barometric pressure in mm of Hg",Pmm
1310  Pbar=Pmm*.019337
1320  Cdair=.97
1330  Cdhf=.97
1340  Cdho=.97
1350  !ALL THERMOCOUPLES ARE CHROMEL vs. ALUMEL (TYPE K) WITH
1360  !ELECTRONIC ICE POINTS. TEMPERATURE READINGS (VOLTAGES) ARE
1370  !CONVERTED TO DEGREES RANKINE (R) PER "INDUSTRIAL INSTRUMENTATION" BY
1380  !D.P. ECKMAN (PAGE 369). THIS CALCULATION IS PERFORMED IN SUBROUTINE
1390  !Tcalc. TEN VOLTAGE INTERVALS ARE USED BETWEEN 460 AND 2460 R.
1400  PRINT USING "@"
1410  PRINT USING "6/"
1420  INPUT "WILL THE AUGMENTOR TUBE BE USED? (Y/N)",Aug$          !DU
1430  IF Aug$="Y" THEN Aug=1                                      !DU
1440  IF Aug$="N" THEN Aug=0
1450  PRINT USING "@"
1460  PRINT USING "6/"
1470  INPUT "WILL THE AIR HEATER BE USED?  (Y/N)",Zz$
1480  IF Zz$="Y" THEN Ht=1.
1490  IF Zz$="N" THEN Ht=0.
1500  PRINT USING "@"
1510  PRINT USING "6/"
1520  INPUT "WILL YOU USE PRE-INITIALIZED VALUES OF CALIBRATION CONSTANTS AND ZE
ROS? (Y/N)",Zz$
1530  IF Zz$="Y" THEN GOTO Initial
1540  GOTO Transcal
1550 Tcalc:    !
1560  !*****************************************************************
1570  !     ***VOLTAGE TO TEMPERATURE (RANKINE) CONVERSION SUBROUTINE***
1580  !*****************************************************************
1590          IF Volts(.00153 THEN T=((Volts+.00068)/.0000220)+460
1600          IF Volts)=.00153 AND Volts(.00382 THEN T=((Volts-.00153)/.000023
0)+560
1610          IF Volts)=.00382 AND Volts(.00609 THEN T=((Volts-.00382)/.000022
7)+660
1620          IF Volts)=.00609 AND Volts(.00831 THEN T=((Volts-.00609)/.000022
2)+760
1630          IF Volts)=.00831 AND Volts(.01056 THEN T=((Volts-.00831)/.000022
5)+860
1640          IF Volts)=.01056 AND Volts(.01285 THEN T=((Volts-.01056)/.000022
9)+960
1650          IF Volts)=.01285 AND Volts(.01518 THEN T=((Volts-.01285)/.000023
3)+1060
1660          IF Volts)=.01518 AND Volts(.01752 THEN T=((Volts-.01518)/.000023
4)+1160
1670          IF Volts)=.01752 AND Volts(.01988 THEN T=((Volts-.01518)/.000023
6)+1260
```

```
1680          IF Volts)=.01988 AND Volts(.02225 THEN T=((Volts-.01988)/.000023
7)+1360
1690          IF Volts)=.02225 AND Volts(.02463 THEN T=((Volts-.02225)/.000023
8)+1460
1700          IF Volts)=.02463 AND Volts(.02698 THEN T=((Volts-.02463)/.000023
5)+1560
1710          IF Volts)=.02698 AND Volts(.02932 THEN T=((Volts-.02698)/.000023
7)+1650
1720          IF Volts)=.02932 AND Volts(.03165 THEN T=((Volts-.02932)/.000023
3)+1760
1730          IF Volts)=.03165 AND Volts(.03393 THEN T=((Volts-.03165)/.000022
8)+1860
1740          IF Volts)=.03393 AND Volts(.03619 THEN T=((Volts-.03393)/.000022
6)+1960
1750          IF Volts)=.03619 AND Volts(.03843 THEN T=((Volts-.03619)/.000022
4)+2060
1760          IF Volts)=.03843 AND Volts(.04062 THEN T=((Volts-.03843)/.000021
9)+2160
1770          IF Volts)=.04062 AND Volts(.04278 THEN T=((Volts-.04062)/.000021
6)+2260
1780          IF Volts)=.04278 AND Volts(.04491 THEN T=((Volts-.04278)/.000021
6)+2360
1790          IF Volts)=.04491 THEN T=((Volts-.04278)/.0000216)+2460
1800     RETURN
1810 Initial:  !
1820 ! Initialized values of zeros and calibration constants for all transducers
1830 Testno$="BEHRENS"
1840 Date$="1-30-90"
1850 Fuelid$="0007"
1860 Heaterfuel$="HYDROGEN"
1870 Vpa0=.0017222
1880 Kpa=33262.88
1890 Vpc0=-.176573
1900 Kpc=844.814
1910 Vpho0=.0356869
1920 Kpho=671.61413
1930 Vphf0=-.116253
1940 Kphf=1356.9902
1950 Kmfuel=.5
1960 Transcal: !
1970     !************************************************************
1980     !(2) TRANSDUCER CALIBRATIONS
1970     !************************************************************
2000     !THERE ARE 4 PRESSURE TRANSDUCERS THAT MUST BE CALIBRATED
2010     !TRANSDUCER LINEARITY MUST BE VERIFIED BEFORE THIS
2020     !CALIBRATION PROCEDURE IS EMPLOYED. THE ORDER OF CALIBRATION IS AS
2030     !FOLLOWS: Pa, Pc, Phf, Pho
2040     !THE FOLLOWING TWO LINES SET UP 722 AND 709 FOR DATA ACQUISITION"
2050     !CLEAR 709
2060     CLEAR 722
2070     REMOTE 709
2080     OUTPUT 722;"L1R11STNZ110STIT4QX1"
2090     INPUT "DO YOU WANT TO CALIBRATE TRANSDUCERS? (Y/N)",Yy$
2100     IF Yy$="N" THEN GOTO Endcal
2110     INPUT "DO YOU WANT CONSECUTIVE ORDER OF CALIBRATION?(Y/N)",Yy$
2120     IF Yy$="Y" THEN GOTO Consec
2130     INPUT "DO YOU WANT TO RECALIBRATE Pa? (Y/N)",Yy$
2140     IF Yy$="Y" THEN GOTO Pacal
2150     PRINT USING "@"
2160 Pc: !
```

```
2170  INPUT "DO YOU WANT TO RECALIBRATE Pc? (Y/N)",Yy$
2180  IF Yy$="Y" THEN GOTO Pccal
2190  PRINT USING "@"
2200  IF Ht=0 THEN GOTO Endcal
2210 Phf:                    !
2220  INPUT "DO YOU WANT TO RECALIBRATE Phf? (Y/N)",Yy$
2230  IF Yy$="Y" THEN GOTO Phfcal
2240  PRINT USING "@"
2250 Pho:                    !
2260  INPUT "DO YOU WANT TO RECALIBRATE Pho? (Y/N)",Yy$
2270  IF Yy$="Y" THEN GOTO Phocal
2280  GOTO Endcal
2290 Consec:                 !
2300  Cons=1
2310 Pacal: !
2320  !****************************************************************
2330  PRINT USING "2/"
2340  PRINT "** CALIBRATION OF Pa, THE AIR SONIC CHOKE PRESSURE TRANSDUCER**"
2350  PRINT USING "2/"
2360  !****************************************************************
2370 Pa0cal:  !
2380  PRINT " ***** Z E R O   P R E S S U R E *****"
2390  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2400  DISP "HIT CONTINUE WHEN READY TO TAKE ZERO READING"
2410  PAUSE
2420  REMOTE 709
2430  OUTPUT 709;"AC24"
2440  WAIT 2
2450  OUTPUT 722;"T3"
2460  ENTER 722;Vpa0
2470  PRINT "Vpa0=";Vpa0
2480  BEEP
2490  INPUT "READING OK? (Y/N)",Zz$
2500  IF Zz$="N" THEN GOTO Pa0cal
2510 Pamaxcal:  !
2520  PRINT USING "@"
2530  PRINT "    ***** C A L I B R A T I O N *****"
2540  PRINT "APPLY MAXIMUM PRESSURE USING THE DEAD-WEIGHT TESTER"
2550  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pamax
2560  DISP "HIT CONTINUE WHEN READY"
2570  PAUSE
2580  REMOTE 709
2590  OUTPUT 709;"AC24"
2600  WAIT 2
2610  OUTPUT 722;"T3"
2620  ENTER 722;Vpamax
2630  PRINT "Vpamax=";Vpamax,"Pamax= ";Pamax
2640  Kpa=(Pamax)/(Vpamax-Vpa0)
2650  PRINT "Kpa= ";Kpa
2660  BEEP
2670  INPUT "READING OK? (Y/N)",Zz$
2680  IF Zz$="N" THEN GOTO Pamaxcal
2690  IF Cons=1 THEN GOTO Pccal
2700 Pccal: !
2710  !****************************************************************
2720  PRINT USING "@"
2730  PRINT "**CALIBRATION OF Pc, THE T63 CHAMBER PRESSURE TRANSDUCER**"
2740  !****************************************************************
2750 Pc0cal:  !
2760  PRINT "**** ZERO PRESSURE ****"
2770  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2780  DISP "HIT CONTINUE WHEN READY"
```

```
2790  PAUSE
2800  REMOTE 709
2810  OUTPUT 709;"AC23"
2820  WAIT 2
2830  OUTPUT 722;"T3"
2840  ENTER 722;Vpc0
2850  PRINT "Vpc0=";Vpc0
2860  BEEP
2870  INPUT "READING OK?  (Y/N)",Zz$
2880  IF Zz$="N" THEN GOTO Pc0cal
2890  Pcmaxcal:  !
2900  PRINT USING "@"
2910  PRINT " **** CALIBRATION  ****"
2920  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2930  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pcmax
2940  DISP "HIT CONTINUE WHEN READY"
2950  PAUSE
2960  REMOTE 709
2970  OUTPUT 709;"AC23"
2980  WAIT 2
2990  OUTPUT 722;"T3"
3000  ENTER 722;Vpcmax
3010  PRINT "Vpcmax=";Vpcmax,"Pcmax=";Pcmax
3020  Kpc=Pcmax/(Vpcmax-Vpc0)
3030  PRINT "Kpc= ";Kpc
3040  BEEP
3050  INPUT "READING OK? (Y/N)",Zz$
3060  IF Zz$="N" THEN GOTO Pcmaxcal
3070  IF Ht=0, THEN GOTO Fincal
3080  IF Cons=1 THEN GOTO Phfcal
3090  GOTO Phf
3100  Phfcal:!
3110  !********************************************************************
3120  PRINT USING "@"
3130  PRINT "**CALIBRATION OF Phf , THE T63 AIR HEATER FUEL TRANSDUCER **"
3140  !********************************************************************
3150  Phf0cal:  !
3160  PRINT "****ZERO PRESSURE****"
3170  PRiNT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3180  DISP "HIT CONTINUE WHEN READY"
3190  PAUSE
3200  REMOTE 709
3210  OUTPUT 709;"AC22"
3220  WAIT 2
3230  OUTPUT 722;"T3"
3240  ENTER 722;Vphf0
3250  PRINT "Vphf0=";Vphf0
3260  BEEP
3270  INPUT "READING OK?  (Y/N)",Zz$
3280  IF Zz$="N" THEN GOTO Phf0cal
3290  Phfmaxcal:  !
3300  PRINT USING "@"
3310  PRINT "****CALIBRATION****"
3320  DISP "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3330  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phfmax
3340  DISP "HIT CONTINUE WHEN READY"
3350  PAUSE
3360  REMOTE 709
3370  OUTPUT 709;"AC22"
3380  WAIT 2
```

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```
3390 OUTPUT 722;"T3"
3400 ENTER 722;Vphfmax
3410 PRINT "Vphfmax=";Vphfmax,"Phfmax=";Phfmax
3420 Kphf=Phfmax/(Vphfmax-Vphf0)
3430 PRINT "Kphf=";Kphf
3440 BEEP
3450 INPUT "READING OK? (Y/N)",Zz$
3460 IF Zz$="N" THEN GOTO Phfmaxcal
3470 IF Cons=1 THEN GOTO Phocal
3480 GOTO Pho
3490 Phocal:!
3500 !*********************************************************************
3510 PRINT USING "@"
3520 PRINT "**CALIBRATION OF Pho, THE AIR HEATER OXYGEN PRESSURE TRANSDUCER**"
3530 !*********************************************************************
3540 Pho0cal:  !
3550 PRINT "****ZERO CALIBRATION****"
3560 PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3570 DISP "HIT CONTINUE WHEN READY"
3580 PAUSE
3590 REMOTE 709
3600 OUTPUT 709;"AC21"
3610 OUTPUT 722;"T3"
3620 ENTER 722;Vpho0
3630 PRINT "Vpho0=";Vpho0
3640 INPUT "READING OK?  (Y/N)",Zz$
3650 IF Zz$="N" THEN GOTO Pho0cal
3660 Phomaxcal:  !
3670 PRINT USING "@"
3680 PRINT "****CALIBRATION****"
3690 PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3700 INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phomax
3710 DISP "HIT CONTINUE WHEN READY"
3720 PAUSE
3730 REMOTE 709
3740 OUTPUT 709;"AC21"
3750 OUTPUT 722;"T3"
3760 ENTER 722;Vphomax
3770 PRINT "Vphomax=";Vphomax,"Phomax=";Phomax
3780 Kpho=Phomax/(Vphomax-Vpho0)
3790 PRINT "Kpho=";Kpho
3800 BEEP
3810 INPUT "READING OK? (Y/N)",Zz$
3820 IF Zz$="N" THEN GOTO Phomaxcal
3830 IF Aug=1 THEN GOTO Augcal
3840 Endcal:                    !
3850 Fincal: !
3860 PRINT USING "@"
3870 PRINT "THIS ENDS THE CALIBRATIONS "
3880 !*********************************************************************
3890 !(C) PRE-RUN INPUTS, FLOW RATE CHECKS AND NOZZLE CALCULATIONS
3900 !*********************************************************************
3910 !*********************************************************************
3920 ! A. FLOW RATE SET-UPS AND CHECKS
3930 !*********************************************************************
3940 PRINT USING "@"
3950 INPUT "DO YOU WANT TO PRESET THE AIR FLOW RATE?(Y/N)",Zz$
3960 IF Zz$="N" THEN GOTO Paskip
3970 PRINT "SET THE DESIRED VALUE OF Pa(psig) USING THE HAND LOADER /PRESSURE G
AGE"
3980 PRINT USING "3/"
3990 PRINT "THE HAND LOADER SHOULD BE 20 PSIG MORE THAN DESIRED PRESSURE"
```

```
4000 Paset: !
4010   PRINT USING "3/"
4020   PRINT "MANUALLY INITIATE AIR FLOW BY TURNING 'MAIN AIR' ON CONTROL PANEL"
4030   PRINT USING "2/"
4040   DISP "HIT CONTINUE WHEN READY"
4050   PAUSE
4060   WAIT 3
4070   OUTPUT 709;"AC24"
4080   OUTPUT 722;"T3"
4090   ENTER 722;Vpa
4100   OUTPUT 709;"AC60"
4110   OUTPUT 722;"T3"
4120   ENTER 722;Vta
4130   OUTPUT 709;"AC61"
4140   OUTPUT 722;"T3"
4150   ENTER 722;Vti
4160   BEEP
4170   PRINT USING "@"
4180   PRINT "TURN OFF 'MAIN AIR'"
4190   DISP "HIT CONTINUE TO PROCEED"
4200   PAUSE
4210   Pa=(Vpa-Vpa0)*Kpa+Pbar
4220   Volts=Vta
4230   GOSUB Tcalc
4240   Ta=T
4250   Volts=Vti
4260   GOSUB Tcalc
4270   Tcin=T
4280   Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
4290   Bpair=Kmair*Cdair*Pa*.7854*(Dbpchoke^2)/(Ta^.5)
4300   PRINT USING "@"
4310   PRINT USING "5A,2X,DDD.DDDD";"Mair=";Mair
4320   PRINT USING "14A,DDD.DDD";"Mair DESIRED=";Maird
4330   Ratio=Mair/Maird
4340   PRINT USING "20A,D.DDD,2X,3A,1X,DDDD.D,1A,3X,3A";"Mair/DESIRED Mair=";Rat
io,"Ta=";Ta,"R"
4350   PRINT USING "6A,2X,DDD.DDDD";"BPair=";Bpair
4360   Pg=Pa-Pbar
4370   PRINT USING "4A,DDDD.D,6A";"Pa =";Pg;"  Psig"
4380   PRINT USING "4A,DDDD.D,3A";"Ta =";Ta;"  R"
4390   INPUT "IS AIR FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
4400   IF Xx$="Y" THEN GOTO Prerun
4410   Panew=(Pa*Maird/Mair)-Pbar
4420   PRINT "RESET Pa TO";Panew;"Psig"
4430   DISP "HIT CONTINUE AFTER RESET OF Pa"
4440   PAUSE
4450   GOTO Paset
4460 Prerun:    !
4470   INPUT "DO YOU WANT PRINTOUT OF PRE-RUN DATA?(Y/N)",Xx$
4480   IF Xx$="Y" THEN GOTO Preprint
4490   GOTO Skipprint
4500 Preprint:    !
4510             PRINTER IS 701
4520   PRINT "              **** PRE-RUN DATA, USING AIR ONLY   ****"
4530   PRINT ""
4540   PRINT "DATE:    ";Date$
4550   PRINT USING "3A,DDDD.D,6A";"Pa=";Pa," Psia"
4560   !PRINT USING "3A,DDD.D,3A";"Tcin=";Tcin,"  R"
4570   PRINT USING "5A,D.DDDD,11A";"Mair=";Mair,"  (Lbm/sec)"
4580   PRINT USING "5A,D.DDDD,11A";"BPair=";Bpair,"  (lbm/sec)"
```

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```
4590   PRINTER IS 1
4600 Skipprint: !
4610   DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
4620   PAUSE
4630 Paskip:    !
4640             IF Ht=0 THEN GOTO Phoskip
4650   PRINT USING "@"
4660   INPUT "DO YOU WANT TO PRESET THE HEATER FUEL FLOW RATE? (Y/N)",Zz$
4670   IF Zz$="N" THEN GOTO Phfskip
4680 !*********************************************************************
4690   PRINT "SET THE DESIRED VALUE OF Phf USING THE HAND LOADER/PRESSURE GAGE"
4700 !*********************************************************************
4710   DISP "HIT CONTINUE WHEN READY"
4720   PAUSE
4730 Phfset: !
4740   PRINT USING "@"
4750   PRINT "MANUALLY TURN ON AIR 'HEATER FUEL' SWITCH"
4760   DISP " HIT CONTINUE TO PROCEED"
4770   PAUSE
4780   OUTPUT 709;"AC22"
4790   OUTPUT 722;"T3"
4800   ENTER 722;Vphf
4810   OUTPUT 709;"AC65"
4820   OUTPUT 722;"T3"
4830   ENTER 722;Vthf
4840   !CLEAR 709
4850   PRINT "MANUALLY TURN OFF AIR 'HEATER FUEL' SWITCH"
4860   BEEP
4870   DISP "HIT CONTINUE TO PROCEED"
4880   PAUSE
4890   Phf=(Vphf-Vphf0)*Kphf+Pbar
4900   Volts=Vthf
4910   GOSUB Tcalc
4920   Thf=T
4930   Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
4940   PRINT USING "@"
4950   PRINT USING "4A,DD.DDDDD";"Mhf=";Mhf
4960   PRINT USING "12A,DD.DDDDD";"Mhf DESIRED=";Mhfd
4970   Ratio=Mhf/Mhfd
4980   PRINT USING "18A,D.DDD,2X,4A,DDDD.DD,1A";"Mhf/ Mhf DESIRED=";Ratio,"Thf="
;Thf,"R"
4990   Pg=Phf-Pbar
5000   PRINT USING "5A,DDDD.DDD,4A,3X,4A,DDDD.DD,1A,4A,DDDD.DD,1A";"Phf= ";Pg;"P
sig","Thf=";Thf;"R"
5010   INPUT "IS HEATER FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
5020   IF Xx$="Y" THEN GOTO Phffin
5030   Phfnew=(Phf*Mhfd/Mhf)-Pbar
5040   PRINT USING "13A,DDDD.DD,4A";"RESET Phf TO";Phfnew;"Psig"
5050   DISP "HIT CONTINUE AFTER RESET OF Phf"
5060   PAUSE
5070   GOTO Phfset
5080 Phffin: !
5090   DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
5100   PAUSE
5110 Phfskip:    !
5120   PRINT USING "@"
5130   INPUT "DO YOU WANT TO PRESET THE HEATER OXYGEN FLOW RATE?(Y/N)",Zz$
5140   IF Zz$="N" THEN GOTO Fhoskip
5150   !*********************************************************************
5160   PRINT "SET THE DESIRED VALUE OF Pho USING THE HAND LOADER/PRESSURE GAGE"
5170   !*********************************************************************
5180 Phoset: !
5190         PRINT "MANUALLY TURN ON AIR 'HEATER OXYGEN' SWITCH"
5200         DISP "HIT CONTINUE TO PROCEED"
```

```
5210        PAUSE
5220        OUTPUT 709;"AC21"
5230        OUTPUT 722;"T3"
5240        ENTER 722;Vpho
5250        OUTPUT 709;"AC64"
5260        OUTPUT 722;"T3"
5270        ENTER 722;Vtho
5280        PRINT "MANUALLY TURN OFF AIR 'HEATER OXYGEN' SWITCH"
5290        BEEP
5300        DISP "HIT CONTINUE TO PROCEED"
5310        PAUSE
5320        Pho=(Vpho-Vpho0)*Kpho+Pbar
5330        Volts=Vtho
5340        GOSUB Tcalc
5350        Tho=T
5360        Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
5370        PRINT USING "@"
5380        PRINT USING "4A,DD.DDDDD";"Mho=";Mho
5390        PRINT USING "18A,DD.DDDDD";"Mho DESIRED=";Mhod
5400        Ratio=Mho/Mhod
5410        Pg=Pho-Pbar
5420        PRINT USING "5A,DDDD.DD,1X,5A,5X,4A,DDDD.DD,1X,2A";"Pho=";Pg;"Psig";
"Tho=";Tho;"R"
5430        INPUT "IS THE HEATER OXYGEN FLOW RATE ENOUGH? (Y/N)?",Xx$
5440        IF Xx$="Y" THEN GOTO Phoskip
5450        Phonew=(Pho*Mhod/Mho)-Pbar
5460        PRINT USING "14A,DDDD.DD,1X,4A";"RESET Pho  TO ";Phonew;"Psig"
5470        DISP "HIT CONTINUE AFTER RESET OF Pho"
5480        PAUSE
5490        GOTO Phoset
5500 Phoskip:   !
5510        PRINT "THIS COMPLETES PRE-RUN SET-UP"
5520 !***************************************************************************
5530 ! (4) THIS PORTION OF THE PROGRAM RUNS THE TEST AND COLLECTS THE DATA
5540 !***************************************************************************
5550 ! PRINT USING "@"
5560    DISP "SET TIMEDATE BY PRESSING K19 AND UPDATE, THEN EXECUTE, THEN HIT CON
TINUE"
5570    BEEP
5580    PAUSE
5590    PRINT USING "@"
5600 Rpt:  !
5610          PRINTER IS 1
5620    ! THE FOLLOWING PROGRAMS THE 3456 DVM
5630    ASSIGN @Scanner TO 709
5640    ASSIGN @Svm TO 722
5650    CLEAR @Svm
5660    OPTION BASE 1
5670    DIM Press(10,5)
5680    DIM Temp(10,6)
5690    DIM Augtemp(10,3)
5700    CLEAR @Svm
5710    OUTPUT @Svm;"L1Z1D0S0F1R3OSTD1STNP0FL01STIS01T401QX1"
5720    DISP "HIT CONTINUE FOR HOT RUN DATA"
5730    BEEP
5740    PAUSE
5750    DISP ""
5760    GOSUB Press
5770    GOSUB Tem
5780    IF Aug=1 THEN GOSUB Aug
5790    GOTO Shutdown
```

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```
5800    !###############################################################
5810 Press:         !
5820    PRINT USING "@"
5830    PRINT USING "10/"
5840    PRINT "    ***********  COLLECTING PRESSURE    ***********"
5850    PRINT ""
5860    PRINT "    ***********  COLLECTING PRESSURE    ***********"
5870       OUTPUT @Scanner;"AC21AF21AL25AE2"
5880       WAIT .2
5890       OUTPUT @Svm;"50STNT3"
5900       ENTER @Svm USING "#,K";Press(*)
5910       !                                    SUBROUTINE Press
5920    OUTPUT @Svm;"1STNT4"
5930    RETURN
5940    !###############################################################
5950 Aug:    ! TEMPERATURE COLLECTING ROUTINE FOR AUGMENTOR TUBE
5960    PRINT "*** COLLECTING AUGMENTOR TEMPERATURES  ****"
5990       OUTPUT @Scanner;"AC66AF66AL6BAE2"
5991       OUTPUT @Svm;"30STNR2T3"
5992       WAIT .2
6000       ENTER @Svm USING "#,K";Augtemp(*)
6010       OUTPUT @Svm;"R31STNT4"
6020       RETURN
6030    !###############################################################
6040 Tem:    !
6050    PRINT " *****COLLECTING TEMPERATURES ******"
6060       OUTPUT @Svm;"60STNR2"
6070       OUTPUT @Scanner;"AC60AF60AL65AE2"
6080       WAIT .2
6090       OUTPUT @Svm;"60STNR2T3"
6100       ENTER @Svm USING "#,K";Temp(*)
6110    OUTPUT @Svm;"1STNR3T4"
6120    RETURN
6130    !###############################################################
6140 Shutdown:  !
6150           PRINT USING "@"
6160           PRINT " TEST COMPLETE: TURN OFF MAIN-AIR, HEATER GASES "
6170 !**************************************************************************
6180 !* (5) POST-RUN OPERATION, DATA REDUCTION AND SHUTDOWN
6190 !**************************************************************************
6200           DISP "HIT CONTINUE TO PROCEED TO DATA REDUCTION"
6210           BEEP
6220           PAUSE
6230       PRINTER IS 701
6240    PRINT USING "3/"
6250    PRINT "                    ****  PRE-RUN INPUT   **** "
6260    PRINT USING "2/"
6270    PRINT USING "14A,7A,5X,14A,9A,5X,14A,9A";"Testno=";Testno$,"Date=";Date$,"
Fuelid=";Fuelid$
6280    PRINT USING "14A,9A";"Heaterfuel=";Heaterfuel$
6290    PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD";"Dairchoke=";Dairchoke,"Dhtfuch
oke=";Dhfchoke
6300    PRINT USING "14A,DDDD.DDDD";"Dhtoxchoke=";Dhochoke
6310    PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD,7X,14A,DDDD.DDD";"Cdair=";Cdair,
"Cdh=";Cdhf,"Cdho=";Cdho
6320    PRINT USING "14A,DDDD.DDD,5X,14A,DDDD.DDD,5X,14A,DDDD.DDD";"Gammahf=";Gamm
ahf
6330    PRINT USING "14A,DDDD.DD,5X,14A,DDDD.DD,5X,14A,DDDD.DD";"Rhf=";Rhf
6340    PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmhf=";Kmhf
6350    PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmho=";Kmho,"Kmair=";Kmair
```

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6360   PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.D";"Maird=";Maird,"Tcind=";Tcind
6370   PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,4X,14A,DDDD.D
DDD";"Mhfd=";Mhfd,"Mhod=";Mhod,"Mfueld=";Mfueld
6380   PRINT USING "14A,DDDDD.DDDD,5X,14A,DDDDD.DDDD,5X,14A,DDDDD.DDDD,5X,14A,DDD
D.DDDD";"Kpa=";Kpa,"Vpa0=";Vpa0,"Kpc=";Kpc,"Vpc0=";Vpc0
6390   PRINT USING "3/"
6400   PRINT ""
6410   PRINT USING "35X,28A";"****  DATA  EXTRACTED   ****"
6420   PRINT ""
6430   PRINT USING "120A";"FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec,
PRESSURE IN Psia, TEMPERATURES IN R"
6440      PRINT USING "5A,6X,6A,5X,6A,7X,6A,9X,6(7A,5X)";"Count","Mair","Mbpair
","Mfuel","f","Mhf","Mho","Phf","Pho","Pc"
6450    FOR J=1 TO 10
6460      Vpa=Press(J,4)
6470      Pa=(Vpa-Vpa0)*Kpa+Pbar
6480      Vpc=Press(J,3)
6490      Pc=(Vpc-Vpc0)*Kpc+Pbar
6500      Vmfuel=Press(J,5)
6510      Mfuel=Vmfuel*Kmfuel
6520      IF Ht=1 THEN
6530       Vphf=Press(J,2)
6540       Phf=(Vphf-Vphf0)*Kphf+Pbar
6550       Vpho=Press(J,1)
6560       Pho=(Vpho-Vpho0)*Kpho+Pbar
6570      END IF
6580      Volts=Temp(J,1)
6590      GOSUB Tcalc
6600      Ta=T
6610      IF Ht=1 THEN
6620       Volts=Temp(J,5)
6630       GOSUB Tcalc
6640       Tho=T
6650       Volts=Temp(J,6)
6660       GOSUB Tcalc
6670       Thf=T
6680      END IF
6690      !
6700      Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
6710      Bpair=Kmair*Cdair*Pa*.7854*(Dbpchoke^2)/(Ta^.5)
6720      F=.108*Mfuel/Mair
6730      IF Ht=0. THEN GOTO Jump
6740      IF Phf<=(Pc*2) THEN Mhf=0.
6750      IF Pho<=(Pc*2) THEN Mho=0.
6760      Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
6770      Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
6780 Jump:  !
6790          IF Ht=0. THEN
6800              Phf=0
6810              Pho=0
6820              Mhf=0
6830              Mho=0
6840          END IF
6850      ! THE VALUES BELOW ARE DEFAULT VALUES TO PREVENT PRINTER ERRORS
6860      IF Mair<.0001 THEN Mair=.0001
6870      IF Bpair<.0001 THEN Bpair=.0001
6880      IF Mfuel<.0001 THEN Mfuel=.0001
6890      IF F<.0001 THEN F=.0001
6900      IF Mhf<.0001 THEN Mhf=.0001
6910      IF Mho<.0001 THEN Mho=.0001
6920      IF Phf<.0001 THEN Phf=.0001
6930      IF Pho<.0001 THEN Pho=.0001
6940      IF Pc<.0001 THEN Pc=.0001
```

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```
6950    IF Mair)2000. THEN Mair=2000.
6960    IF Bpair)2000. THEN Bpair=2000.
6970    IF Mfuel)2000. THEN Mfuel=2000.
6980    IF F)2000. THEN F=2000.
6990    IF Mhf)2000. THEN Mhf=2000.
7000    IF Mho)2000. THEN Mhf=2000.
7010    IF Phf)2000. THEN Phf=2000.
7020    IF Pho)2000. THEN Pho=2000.
7030    IF Pc)2000. THEN Pc=2000.
7040    PRINT USING "DDD,3X,MD.DDDE  ,3X,MD.DDDE  ,3X,MD.DDDE  ,3X,3(MD.DDDE  ,3X
),3(MDD.DDE  ,3X),1X";J,Mair,Bpair,Mfuel,F,Mhf,Mho,Phf,Pho,Pc
7050    NEXT J
7060       PRINT ""
7070       PRINT USING "5A,5X,9(7A,7X)";"Count","Ta","Tcin","Tex1","Tex2","Taugup
","Taugd1","Taugd2"
7080       FOR J=1 TO 10
7090       Volts=Temp(J,1)
7100         GOSUB Tcalc
7110         Ta=T
7120       Volts=Temp(J,2)
7130         GOSUB Tcalc
7140         Tcin=T
7150       Volts=Temp(J,3)
7160         GOSUB Tcalc
7170         Tex1=T
7180       Volts=Temp(J,4)
7190         GOSUB Tcalc
7200         Tex2=T
7210       Volts=Avgtemp(J,1)
7220         GOSUB Tcalc
7230         Taugup=T
7240       Volts=Avgtemp(J,2)
7250         GOSUB Tcalc
7260         Taugd1=T
7270       Volts=Avgtemp(J,3)
7280         GOSUB Tcalc
7290         Taugd2=T
7300       IF Ta(100. THEN Ta=100.
7310       IF Tcin(100. THEN Tcin=100.
7320       IF Tex1(100. THEN Tex1=100.
7330       IF Tex2(100. THEN Tex2=100.
7340       IF Taugup(100. THEN Taugup=100.
7350       IF Taugd1(100. THEN Taugd1=100.
7360       IF Taugd2(100. THEN Taugd2=100.
7370       IF Ta)4000. THEN Ta=4000.
7380       IF Tcin)4000. THEN Tcin=4000.
7390       IF Tex1)4000. THEN Tex1=4000.
7400       IF Tex2)4000. THEN Tex2=4000.
7410       IF Taugup)4000. THEN Taugup=4000.
7420       IF Taugd1)4000. THEN Taugd1=4000.
7430       IF Taugd2)4000. THEN Taugd2=4000.
7440       PRINT USING "DDD,3X,7(MDD.DDE,4X)";J,Ta,Tcin,Tex1,Tex2,Taugup,Taugd1,T
augd2
7450       NEXT J
7460    GOTO Finish
7470 Finish:     !
7480    PRINTER IS 1
7490    PRINT USING "@"
7500    PRINT "DATA OUTPUT IS COMPLETE"
7510    DISP "SECURE TEST CELL !!!"
7520    BEEP
7530    PAUSE
7540    END
```

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APPENDIX B

RUN CHECKLIST

TEST CELL #1

1. Ensure yellow and top blue air valves in the solid fuel ramjet test cell are closed.

2. Open lower blue valve (opens air line to Test Cell #2 or T-63).

** Note - At least one valve should be open at all times from the main air line to ensure an air vent in case of an accidental component failure.

NITROGEN BOTTLE ROOM

1. Fully open the control room nitrogen bottle. Ensure that there is at least 1000 psi available.

2. Fully open actuator nitrogen bottle. Ensure that there is at least 500 psi available.

CONTROL ROOM

1. Ensure AC master switch is on and the red covered main air switch is closed on the solid fuel ramjet control panel.

2. Ensure there is no pressure set on the gauge on the Air Heater console (the air flow set pressure).

3. Ensure that the T-63 combustion chamber safety thermocouple is installed and operating.

4. Ensure that the fuel tank set pressure (gauge on panel) is less than 500 psi.

FUEL STORAGE ROOM

1. Open nitrogen bottle valve (need at least 400 psi more pressure available in the bottle than the desired fuel line/tank pressure, or 900 psi minimum).

2. Adjust hand loader to read 700 psi.

3. Slowly open the nitrogen gas supply valve located behind the fuel tank near the wall.

4. Very slowly open the fuel line valve from near the bottom of the tank to the T-63.

OUTSIDE/CONTROL ROOM

1. Open main air valve to full open (ensure that there is at least 2500 psi available in outdoor air storage tanks for a run.

2. Ensure all thermocouples are turned on (if required) and pressure transducers and tubing are secure at the test stand.

3. The heated sample line temperature control box should be set to 275 deg. F and the gas analyzers in the control room should be up and operating. The three main switches for the electronic equipment racks should be ON.

4. Load and run the "T63NOX" computer program on the HP microcomputer. The pressure transducers should be calibrated if not already done so, and zeros and constants entered.

5. Set the main air pressure to 600 psi using the hand loader.

6. Set the fuel tank pressure to 500 psi using the hand loader.

7. Go through the flow rate set procedures in accordance with the computer program. This may require opening and resetting the pressures for the air heater fuel and torch gases as well as the heater oxygen tanks in the test cell.

8. Ensure printer is "on-line".

9. Check for personnel near the test cell and for golfers. Activate exterior warning horn and check main air flow rate as cued by the computer.

10. Turn on rocket motor siren.

11. Start strip chart recorder and mark zero/ambient conditions.

12. Activate main air ON.

13. Turn on air heater fuel and heater torch (momentary) until light-off, if required.

14. Ensure T-63 engine ignitor key is installed and in the ON position.

15. Simultaneously, activate the toggled engine ignitor switch and fuel switch. Check desired fuel flow rate (0.33 GPM). Watch for wet or hot start by visually observing exhaust smoke at rig and monitoring the digital combustion chamber safety temperature readout (commence shutdown if temperature reaches 1380 deg. F)

16 When steady-state operation is reached, begin traversing the Kiel probe in the augmentor tube and obtain analyzer measurements.

17. After data gathered, switch fuel OFF and air heater OFF (if applicable). Leave main air ON until engine and augmentor tube are cool.

18. Turn main air OFF, record run time, and calculate fuel used during run. Update fuel board in fuel storage room.

19. Isolate fuel tank with valves and bleed excess fuel in lines with fuel switch activation.

20. Secure all torch and air heater gas bottles in test cell.

21. Close main air valve outside.

22. Vent fuel tank from control panel if desired and close fuel tank nitrogen bottle.

23. Bleed remaining air heater and torch gases from lines and vent with remaining main air in lines. Back off pressure loaders to zero in the control room.

24. Secure analyzers, complete shutdown, and reduce data.

APPENDIX C

HOT RUN DATA

DATE: 3-14-90
Pa= 573.1 Psia
Mair=1.9048 (Lbm/sec)
BPair .6168 (lbm/sec)

RUN #1 - No air heater
No catalyst used

**** PRE-RUN INPUT ****

Testno=	BEHRENS	Date=	3-14-90	Fuelid=	0007
Heaterfuel=	HYDROGEN				
Dairchoke=	.420	Dhtfuchoke=	.040		
Dhtoxchoke=	.0700				
Cdair=	.970	Cdh=	.970	Cdho=	.970
Gammahf=	1.405				
Rhf=	766.50				
Knhf=	.1405				
Kmho=	.5589	Kmair=	.5320		
Maird=	1.900	Tcind=	0.0		
Mhfd=	.0028	Mhod=	.0238	Mfueld=	.3300
Kpa=	33262.8800	Vpau=	.0017	Kpc=	844.8140

Pc
92.43E+00
92.11E+00
92.62E+00
92.28E+00
92.06E+00
92.35E+00
91.24E+00
92.05E+00
91.62E+00
91.42E+00

**** DATA EXTRACTED ****

FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec, PRESSURE IN Psia, TEMPERATURES IN R

Count	Mair	Mbpair	Mfuel	f	Mhf	Mho	Phf	Pho
1	1.922E+00	6.224E-01	3.026E-01	1.700E-02	1.501E-03	8.351E-03	19.94E+01	91.20E+00
2	1.919E+00	6.216E-01	3.039E-01	1.710E-02	1.501E-03	8.351E-03	19.95E+01	91.20E+00
3	1.912E+00	6.191E-01	3.043E-01	1.719E-02	1.504E-03	8.382E-03	19.98E+01	91.54E+00
4	1.913E+00	6.193E-01	3.044E-01	1.719E-02	1.500E-03	8.356E-03	19.93E+01	91.26E+00
5	1.923E+00	6.225E-01	3.045E-01	1.710E-02	1.498E-03	8.375E-03	19.90E+01	91.47E+00
6	1.918E+00	6.211E-01	3.045E-01	1.715E-02	1.501E-03	8.355E-03	19.95E+01	91.25E+00
7	1.920E+00	6.216E-01	3.043E-01	1.712E-02	1.495E-03	8.342E-03	19.86E+01	91.11E+00
8	1.919E+00	6.214E-01	3.043E-01	1.713E-02	1.496E-03	8.389E-03	19.89E+01	91.62E+00
9	1.920E+00	6.216E-01	3.041E-01	1.711E-02	1.496E-03	8.331E-03	19.88E+01	90.99E+00
10	1.922E+00	6.222E-01	3.043E-01	1.710E-02	1.504E-03	8.384E-03	19.98E+01	91.56E+00

Count	Ta	Tcin	Tex1	Tex2	Taugup	Taugd1	Taugd2
1	45.82E+01	46.68E+01	15.50E+02	14.02E+02	90.18E+01	88.52E+01	88.90E+01
2	45.83E+01	46.69E+01	15.51E+02	14.03E+02	90.23E+01	88.54E+01	88.93E+01
3	45.83E+01	46.69E+01	15.52E+02	14.03E+02	90.25E+01	88.57E+01	88.95E+01
4	45.83E+01	46.70E+01	15.52E+02	14.03E+02	90.27E+01	88.59E+01	88.98E+01
5	45.82E+01	46.71E+01	15.51E+02	14.02E+02	90.29E+01	88.62E+01	89.01E+01
6	45.82E+01	46.70E+01	15.51E+02	14.02E+02	90.32E+01	88.65E+01	89.04E+01
7	45.82E+01	46.69E+01	15.50E+02	14.02E+02	90.34E+01	88.67E+01	89.07E+01
8	45.82E+01	46.70E+01	15.51E+02	14.03E+02	90.37E+01	88.70E+01	89.09E+01
9	45.82E+01	46.70E+01	15.50E+02	14.02E+02	90.39E+01	88.73E+01	89.11E+01
10	45.82E+01	46.71E+01	15.50E+02	14.01E+02	90.42E+01	88.76E+01	89.12E+01

**** PRE-RUN DATA, USING AIR ONLY ****

DATE: 3-**-90
Pa= 580.8 Psia
Mair=1.9013 (Lbm/sec)
BPair .6157 (lbm/sec)

RUN #2 - Air heater used
No catalyst

**** PRE-RUN INPUT ****

Testno=	BEHRENS	Date=	3-**-90	Fuelid=	1007	
Heaterfuel=	HYDROGEN					
Dairchoke=	.420	Dhtfuchoke=	.040			
Dhtoxchoke=	.0700					
Cdair=	.970	Cdh=	.970	Cdho=	.970	
Gammahf=	1.405					Pc
Rhf=	766.50					90.11E+00
Kmhf=	.1405					90.00E+00
Kmho=	.5589	Kmair=	.5320			90.28E+00
Maird=	1.900	Tcind=	0.0			90.23E+00
Mhfd=	.0028	Mhod=	.0228	Mfueld=	.3300	90.26E+00
Kpa=	33262.8800	Vpa0=	.0017	Kpc=	844.8140	90.39E+00
						90.11E+00
						89.50E+00
						90.19E+00
						90.27E+00

**** DATA EXTRACTED ****

FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec, PRESSURE IN Psia, TEMPERATURES IN R

Count	Mair	Mbpair	Mfuel	f	Mhf	Mho	Phf	Pho
1	1.959E+00	6.343E-01	1.650E-01	9.096E-03	3.821E-03	1.941E-02	50.44E+01	21.06E+01
2	1.950E+00	6.314E-01	1.651E-01	9.144E-03	3.823E-03	1.940E-02	50.47E+01	21.05E+01
3	1.953E+00	6.323E-01	1.650E-01	9.127E-03	3.823E-03	1.937E-02	50.47E+01	21.02E+01
4	1.955E+00	6.331E-01	1.651E-01	9.118E-03	3.824E-03	1.936E-02	50.48E+01	21.01E+01
5	1.951E+00	6.316E-01	1.649E-01	9.133E-03	3.824E-03	1.933E-02	50.47E+01	20.98E+01
6	1.949E+00	6.310E-01	1.650E-01	9.144E-03	3.825E-03	1.928E-02	50.49E+01	20.93E+01
7	1.952E+00	6.319E-01	1.651E-01	9.135E-03	3.820E-03	1.925E-02	50.42E+01	20.89E+01
8	1.953E+00	6.324E-01	1.649E-01	9.121E-03	3.826E-03	1.924E-02	50.50E+01	20.89E+01
9	1.958E+00	6.341E-01	1.649E-01	9.092E-03	3.826E-03	1.925E-02	50.50E+01	20.88E+01
10	1.949E+00	6.313E-01	1.647E-01	9.122E-03	3.825E-03	1.925E-02	50.48E+01	20.89E+01

Count	Ta	Tcin	Tex1	Tex2	Taugup	Taugd1	Taugd2
1	46.56E+01	76.74E+01	13.75E+02	12.44E+02	89.84E+01	88.46E+01	89.75E+01
2	46.57E+01	76.76E+01	13.75E+02	12.44E+02	89.89E+01	88.49E+01	88.76E+01
3	46.57E+01	76.80E+01	13.74E+02	12.45E+02	89.89E+01	88.50E+01	88.77E+01
4	46.57E+01	76.80E+01	13.74E+02	12.45E+02	89.91E+01	88.51E+01	88.78E+01
5	46.57E+01	76.81E+01	13.74E+02	12.44E+02	89.92E+01	88.52E+01	89.79E+01
6	46.57E+01	76.76E+01	13.74E+02	12.44E+02	89.93E+01	88.53E+01	88.80E+01
7	46.57E+01	76.76E+01	13.72E+02	12.44E+02	89.93E+01	88.53E+01	88.81E+01
8	46.57E+01	76.77E+01	13.72E+02	12.44E+02	89.93E+01	88.55E+01	88.83E+01
9	46.57E+01	76.77E+01	13.71E+02	12.44E+02	89.94E+01	88.56E+01	88.84E+01
10	46.57E+01	76.80E+01	13.71E+02	12.44E+02	89.94E+01	88.56E+01	88.85E+01

DATE: 3-16-90
Pa= 577.2 Psia
Mair=1.8933 (Lbm/sec)
BPair .6131 (lbm/sec)

RUN #3 - No air heater
No catalyst used

**** PRE-RUN INPUT ****

Testno=	BEHRENS	Date=	3-16-90	Fuelid=	0007
Heaterfuel=	HYDROGEN				
Dairchoke=	.420	Dhtfuchoke=	.040		
Dhtoxchoke=	.0700				
Cdair=	.970	Cdh=	.970	Cdho=	.970
Gammahf=	1.405				
Rhf=	766.50				
Kmhf=	.1405				
Kmho=	.5589	Kmair=	.5320		
Maird=	1.900	Tcind=	0.0		
Mhfd=	.0028	Mhod=	.0228	Mfueld=	.3300
Kpa=	33262.8800	Vpa0=	.0017	Kpc=	844.8140

Pc
90.53E+00
90.53E+00
90.86E+00
90.56E+00
89.92E+00
90.56E+00
90.77E+00
90.49E+00
90.56E+00
90.47E+00

**** DATA EXTRACTED ****

FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec, PRESSURE IN Psia, TEMPERATURES IN R

Count	Mair	Mbpair	Mfuel	f	Mhf	Mho	Phf	Pho
1	1.825E+00	5.911E-01	3.223E-01	1.907E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
2	1.826E+00	5.914E-01	3.242E-01	1.917E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
3	1.828E+00	5.919E-01	3.250E-01	1.920E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
4	1.825E+00	5.909E-01	3.251E-01	1.924E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
5	1.827E+00	5.917E-01	3.251E-01	1.921E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
6	1.833E+00	5.937E-01	3.253E-01	1.916E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
7	1.825E+00	5.908E-01	3.251E-01	1.924E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
8	1.825E+00	5.909E-01	3.250E-01	1.924E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
9	1.825E+00	5.911E-01	3.250E-01	1.923E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
10	1.825E+00	5.909E-01	3.250E-01	1.924E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05

Count	Ta	Tcin	Tex1	Tex2	Taugup	Taugd1	Tarod2
1	46.89E+01	47.83E+01	16.94E+02	15.35E+02	99.58E+01	96.78E+01	98.25E+01
2	46.90E+01	47.83E+01	16.94E+02	15.35E+02	99.64E+01	96.21E+01	98.28E+01
3	46.90E+01	47.84E+01	16.93E+02	15.35E+02	99.68E+01	95.73E+01	98.31E+01
4	46.90E+01	47.84E+01	16.93E+02	15.34E+02	99.70E+01	96.27E+01	98.34E+01
5	46.90E+01	47.85E+01	16.92E+02	15.35E+02	99.71E+01	96.79E+01	98.35E+01
6	46.91E+01	47.86E+01	16.92E+02	15.35E+02	99.72E+01	96.68E+01	98.38E+01
7	46.92E+01	47.86E+01	16.92E+02	15.35E+02	99.73E+01	95.69E+01	98.39E+01
8	46.92E+01	47.86E+01	16.93E+02	15.35E+02	99.73E+01	95.78E+01	98.39E+01
9	46.92E+01	47.86E+01	16.93E+02	15.35E+02	99.73E+01	96.38E+01	98.39E+01
10	46.92E+01	47.87E+01	16.95E+02	15.36E+02	99.73E+01	95.84E+01	98.40E+01

**** PRE-RUN DATA, USING AIR ONLY ****

DATE: 3-**1**-90
Pa= 571.9 Psia
Mair=1.8876 (Lbm/sec)
BFair .6112 (lbm/sec)

RUN #4 - No air heater used
                Perlite catalyst installed

**** PRE-RUN INPUT ****

Testno=	BEHRENS	Date=	3-3**1**-90	Fuelid=	0007		
Heaterfuel=	HYDROGEN						
Dairchoke=	.420	Dhtfuchoke=	.040				
Dhtexchoke=	.0700						
Cdair=	.970	Cdh=	.970	Cdho=	.970		
Gammahf=	1.405						
Rhf=	766.50						
Kmhf=	.1405					Pc	
Kmho=	.5589	Kmair=	.5320			94.21E+00	
Maird=	1.900	Tcind=	0.0			93.74E+00	
Mhfd=	.0029	Mhod=	.0228	Mfueld=	.3300	93.45E+00	
Kpa=	33262.8800	Vpa0=	.0017	Kpc=	844.8140	93.54E+00	
						92.85E+00	
						93.74E+00	
						94.18E+00	
						93.83E+00	
						94.55E+00	

**** DATA EXTRACTED ****   93.56E+00

FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec, PRESSURE IN Psia, TEMPERATURES IN R

Count	Mair	Mbpair	Mfuel	f	Mhf	Mho	Phf	Pho
1	1.912E+00	6.191E-01	3.178E-01	1.795E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
2	1.912E+00	6.192E-01	3.196E-01	1.805E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
3	1.916E+00	6.205E-01	3.201E-01	1.804E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
4	1.912E+00	6.192E-01	3.206E-01	1.811E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
5	1.910E+00	6.185E-01	3.209E-01	1.815E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
6	1.912E+00	6.190E-01	3.210E-01	1.814E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
7	1.916E+00	6.205E-01	3.211E-01	1.810E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
8	1.913E+00	6.195E-01	3.210E-01	1.812E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
9	1.913E+00	6.195E-01	3.210E-01	1.812E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05
10	1.918E+00	6.211E-01	3.211E-01	1.808E-02	1.000E-04	1.000E-04	10.00E-05	10.00E-05

Count	Ta	Tcin	Tex1	Tex2	Taugup	Taugd1	Targd2
1	46.37E+01	47.30E+01	15.53E+02	14.14E+02	98.13E+01	72.85E+01	71.38E+01
2	46.38E+01	47.30E+01	15.53E+02	14.14E+02	98.29E+01	72.45E+01	71.39E+01
3	46.39E+01	47.30E+01	15.55E+02	14.14E+03	98.37E+01	72.96E+01	71.42E+01
4	46.39E+01	47.29E+01	15.55E+02	14.14E+02	98.46E+01	72.77E+01	71.43E+01
5	46.39E+01	47.29E+01	15.53E+02	14.13E+02	98.53E+01	72.85E+01	71.43E+01
6	46.39E+01	47.29E+01	15.54E+02	14.14E+02	98.59E+01	72.21E+01	71.43E+01
7	46.38E+01	47.29E+01	15.55E+02	14.15E+02	98.67E+01	71.88E+01	71.44E+01
8	46.37E+01	47.29E+01	15.55E+02	14.16E+02	98.76E+01	71.76E+01	71.45E+01
9	46.37E+01	47.29E+01	15.55E+02	14.16E+02	98.85E+01	72.82E+01	71.49E+01
10	46.36E+01	47.28E+01	15.55E+02	14.17E+02	98.93E+01	73.24E+01	71.50E+01

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